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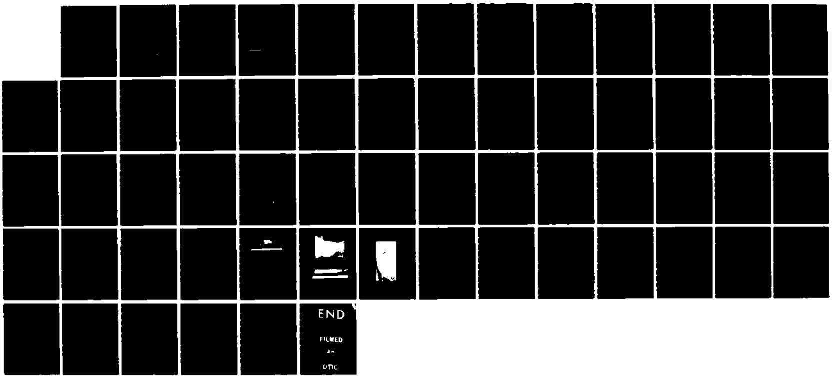

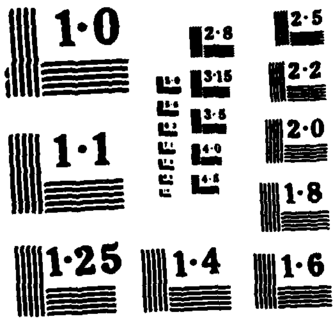

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CHESAPEAKE DIVISION · NAVAL FACILITIES ENGINEERING COMMAND

AD-A163 255

DESIGN GUIDE FOR SELECTION AND SPECIFICATION OF KEVLAR ROPE FOR OCEAN ENGINEERING AND CONSTRUCTION

OCEAN ENGINEERING AND CONSTRUCTION PROJECT OFFICE
CHESAPEAKE DIVISION
NAVAL FACILITIES ENGINEERING COMMAND
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The objective of this design guide is to present information for use in selecting and specifying "Kevlar" aramid ropes for ocean engineering and construction applications.

This guide is based on available technical data which is representative of state-of-the-art knowledge of the material, rope design, manufacturing processes, test procedures and application engineering.

(Abstract Continues)

(Block 20 — Abstract Continued)

The various constructions available are compared with similar constructions of other rope materials including wire rope and comments are made on the relative merits of each for different ocean engineering applications. This comparative data between aramid fiber rope and rope made from other materials is an aid to help support objective decisions by an engineer in selecting rope materials. Since cost factors are important considerations in the selection process, the relative cost of comparable ropes of various materials are established.

In addition, this guide provides information on splices and terminations for aramid rope so that the engineer will understand joint efficiencies, reliability factors and load constraints involved in selecting and specifying splices and terminations. It discusses service considerations such as sheave sizing, abrasion, fake-down requirements, sharkbite protection, environmental exposure and related application information which is needed to specify handling and protective requirements.

DESIGN GUIDE FOR SELECTION AND SPECIFICATION OF KEVLAR ROPE FOR OCEAN ENGINEERING AND CONSTRUCTION

Kenneth M. Ferer
Richard C. Swenson

July 1976

Developed For
CHESAPEAKE DIVISION
NAVAL FACILITIES ENGINEERING COMMAND
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PREFACE

The objective of this design guide is to present information for use in selecting and specifying Kevlar aramid ropes for ocean engineering and construction applications.

This guide is based on available technical data which are representative of state-of-the-art knowledge of the material, rope design, manufacturing processes, test procedures, and application engineering.

It discusses the unique properties of aramid rope, which include:

(a) very low stretch.

(b) high tensile strength.

(c) very high strength-to-weight ratio.

(d) excellent fatigue resistance.

(e) good performance over large temperature range.

(f) low creep.

(g) no shrinkage.

(h) minimum snapback hazard.

(i) good chemical stability.

The negative aspects of the fiber also covered include:

(a) low transverse modulus.

(b) self-abrasion of the fibers.

(c) high material cost.

The various constructions available are compared with similar constructions of other rope materials including wire rope, and comments are made on the relative merits of each for different ocean-engineering applications. These comparative data between aramid fiber rope and rope made from other materials are an aid to help support objective decisions by an engineer in selecting rope materials. Since cost factors are important considerations in the selection process, the relative cost of comparable ropes of various materials are established.

In addition, this guide provides information on splices and terminations for aramid rope so that the engineer will understand joint efficiencies, reliability factors, and load constraints involved in selecting and specifying splices and terminations. It discusses service considerations such as sheave sizing, abrasion, fake-down requirements, sharkbite protection, environmental exposure, and related application information which is needed to specify handling and protective requirements.

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Acknowledgment

Grateful acknowledgment is made to Dr. Paul B. Riewald of Du Pont, Mr. H. Alexander Hood of Wall Rope, and Mr. Simeon Whitehill of Philadelphia Resins, all of whom have been extremely helpful in assembling the material and in reviewing the handbook.

Sources of Tables and Curves

1. E. I. du Pont, Wilmington, Delaware
2. Philadelphia Resins Corporation, Philadelphia, Pennsylvania
3. Wall Rope Works, Beverly, New Jersey
4. Preformed Line Products Company, Cleveland, Ohio
5. Cortland Advanced Product Division, Cortland, New York

CHAPTER 1. KEVLAR ARAMID FIBER

1-1. INTRODUCTION. Kevlar is the registered trademark for a family of aromatic polyamide (aramid) fibers introduced by E. I. du Pont De Nemours and Company, Inc., in 1972. The material's unique chemical structure earned it, and one other Du Pont product (Nomex), the new generic designation of aramid. (In this guidebook, use of the word aramid refers only to Kevlar.) Kevlar aramid fiber has a high tensile strength, a modulus approaching that of steel, more compliance than steel, and dielectric properties near those of glass. Its strength-to-weight ratio is approximately seven times higher than steel in air, and roughly 20 times higher in water. It is corrosion resistant and has low creep characteristics, yet it is as light and as easy to handle as polyester. Moreover, when the fiber is used as a strength member in electromechanical cables, the small amount of elongation under load does not present serious difficulties with regard to electrical conductor stretch. This combination of properties appears to be tailored to the requirements for suspended cable.

Three different types of Kevlar aramid fibers are currently available from Du Pont: Kevlar—formerly Fiber B, Kevlar 29—formerly PRD-49 IV, and Kevlar 49—formerly PRD-49 III. Kevlar was developed primarily for tire reinforcement. Since its properties are similar to those of Kevlar 29, Kevlar will not be discussed separately in this guide. Both Kevlar 29 and Kevlar 49 have many industrial uses other than rope; however, this discussion is limited to aramid ropes.

Both products are available as continuous filament yarns in a range of deniers and finishes. Various cordage and electromechanical cable companies are able to purchase the yarn and to construct several types of general and special application ropes. The fiber can be used as obtained on conventional textile twisting, stranding, or braiding equipment to produce soft yarn cordage as is done with nylon. Some manufacturers impregnate or encapsulate the yarn with a low modulus material such as a polyurethane or neoprene. It also may be used in conventional textile equipment. Another possibility is a more rigid resin impregnation, in which case the strands must be handled like wires in steel rope manufacturing equipment. For electromechanical ropes, electrical conductors can be included during the stranding or braiding process. Finally, the rope can be jacketed for protection. The process of making aramid ropes is no different than for making other types of ropes. However, because of the material's self-abrasion tendencies and its lack of yield prior to rupture, more care must be exercised in its processing.

1-2. ARAMID FIBERS. A rope is a cylindrical symmetrical structure usually circular in cross section. It can transfer tensile loads only along its longitudinal axis. It cannot support any bending, shear, or compressive forces. The mechanical loading characteristics of the rope are directly related to the mechanical loading characteristics of its composite fiber.

The aramid filament, like other synthetic filaments, is anisotropic; the macromolecules are aligned parallel to the fiber axis. Its high tensile strength requires breaking carbon bonds in a longitudinal direction but only molecular van der Waals' forces in a transverse direction. Kevlar 29 has a longitudinal elastic modulus of 12×10^6 lb/in.[2]; Kevlar 49's is 19×10^6 lb/in.[2] The transverse modulus is about two orders of magnitude below the longitudinal modulus, according to Phoenix,[1] although testing by Du Pont indicates the transverse modulus is about one-tenth that of the longitudinal modulus.

Each fiber is produced as a continuous length of material with a diameter of 0.000478 inches (0.00121 centimeters). At the present time, the filaments are a translucent straw color. However, methods are being developed to enable dyeing the filaments. The rope manufacturer may use the yarns as obtained; he may ply several yarns together; or he may induce a slight twist into the yarn. Simple geometry indicates that the strength will decrease as the twist increases; a twisted fiber can form a shear component of force which will weaken it. However, as shown in Figure 1-1, a small twist increases the average break-strength of the yarn due to frictional contact of the filaments and a more even distribution of the tensile load. For example, for a 1,000-denier Kevlar 29 yarn, the optimum amount of twist is approximately 2.5 turns per inch; for 1,500 denier, it is about 2.0 turns per inch; and for 15,000 denier, it is about 0.6 turn per inch.[2] A slight twist does not improve the tensile strength of Kevlar 49 in the same manner. The modulus is too high to accommodate the random slack that is generated in the fibers.

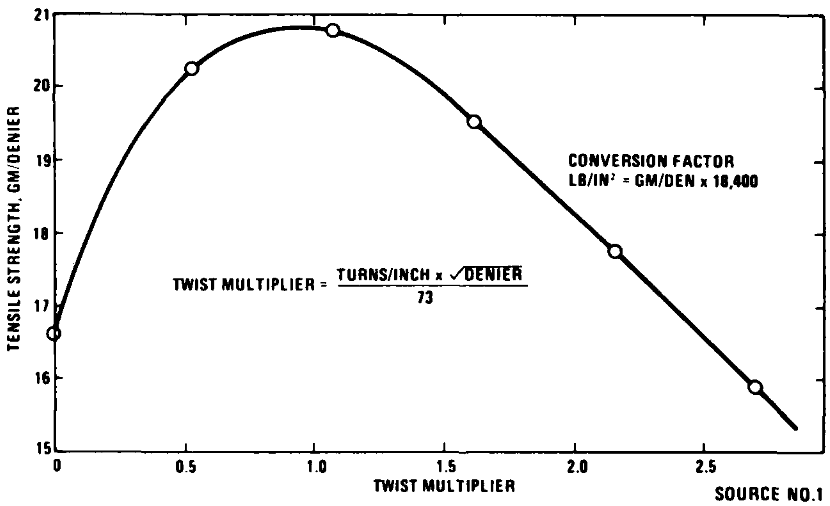

Figure 1-1 — The effect of twist on the tensile strength of Kevlar 29 (textile units)

The designer must determine whether or not to use yarn with a finish applied. The yarn can be obtained with no finish, a standard finish, or a cordage finish. The use determines the one selected. Standard or no-finish yarn is usually chosen when a rope manufacturer wishes to impregnate the yarns with another material. Cordage-finish yarn is the usual selection when soft cordage is to be made directly from Kevlar yarn. It has the best abrasion resistance.

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[1]Phoenix, S. L. "Transverse Mechanical Behavior of Unimpregnated Kevlar 29 Cable Core Under Uniform Radial Loading," Fabric Research Laboratories contract report, 20 June 1974.

[2]"Kevlar 29 Aramid, Product and Product Properties," E. I. du Pont De Nemours and Co., Inc., Wilimington, Delaware.

Several experimental finishes and lubricants are under evaluation which give an improved abrasion resistance to Kevlar 29 and Kevlar 49 yarns. These are described in Section 1-3-2 but are not yet available on yarn supplied by Du Pont.

There exists a certain amount of variation in the mechanical properties of the fiber obtained from Du Pont; however, at this time, there is some argument as to its magnitude. Discussions are being planned on this subject which will pinpoint the causes and enable solutions. Du Pont suggests that the coefficients of variation (standard deviation/mean value) of tensile strength, modulus, and elongation are all about ±3 percent. This is much higher than the deviation normally found in steel wires but only slightly higher than that in other synthetic fibers. Nevertheless, problems do exist; and if one is designing for maximum use, good quality control procedures must be followed. There are no specification callouts at the present time, due to our lack of experience with the material. This handbook is a first step in the learning process, which should lead to the necessary specifications.

1-3. MECHANICAL PROPERTIES OF KEVLAR ARAMID FIBERS

1-3-1. Tensile Strength, Creep, and Modulus of Elasticity. Table 1-1 is a listing of the properties of the Kevlar 29 and Kevlar 49 aramid fibers produced by Du Pont.[3,4] The table shows the density and the ultimate tensile strength of the two yarns to be similar. Notice, though, that the modulus of Kevlar 49 (19×10^6) is higher than that of Kevlar 29 (12×10^6), resulting in a lower elongation. In tensile tests, yarns of either fiber display a nearly linear stress-strain relation.[5] Figure 1-2 compares the stress-stress relationship of various materials to ultimate load.

The yarn can be modeled by a Hookean spring, since the stress-strain curves is linear and since the material exhibits a low creep. Figure 1-3 shows the creep of the Kevlar 29 and Kevlar 49 loaded at 50 percent of ultimate strength.[6] After the initial constructional stretch (which is small) has been removed, the creep in 6 months is less than 0.2 percent for Kevlar 29 and less than 0.1 percent for Kevlar 49. Figure 1-4 gives an extrapolation of the time to rupture versus percentage of ultimate load of Kevlar 49 yarn. The creep properties while the yarn is wet appear to be the same as those while it is dry.

Figure 1-5 is a plot of the specific tensile strength (strength divided by density) versus the specific modulus of elasticity (modulus divided by density) for several fibrous materials. Graphite, for example, is very strong, extremely stiff, and fairly light; therefore, it appears in the upper right portion of the graph. The region of greatest interest, however, is the upper left area of the chart, which includes materials that are very strong, quite light, and neither excessively stiff nor extensible. The aramid fibers appear above the glass fibers because of the greater density of the glass. A comparison of the properties of the various materials for rope construction is summarized in Table 1-2. It is apparent that the new aramid fibers can compete favorably with all existing rope materials.

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[3]Ibid.
[4]"Kevlar 49, Characteristics and Uses of Kevlar 49 Aramid High Modulus Organic Fiber," E. I. du Pont De Nemours and Co., Inc., Wilmington, Delaware.
[5]Riewald, P. G. and Vehkatachalam, T. K., "Kevlar Aramid Fiber for Rope and Cable Applications," *Offshore Technology Conference*, Marine Kevlar Cable Workshop, Houston, Texas, May 1975.
[6]Ibid.

Table 1-1 — Properties of Dry Twisted Kevlar* Yarn

Property	Kevlar 29	Kevlar 49
Density	0.0520 lb/in^3 1.44 gm/cm^3	0.0520 lb/in^3 1.44 gm/cm^3
Filament Diameter	0.00047 in. 0.00121 cm	0.00047 in. 0.00121 cm
Fiber Elongation at Break	4%	2.4%
Tenacity	22 gpd	22 gpd
Tensile Strength	400,000 lb/in^2 28,100 kg/cm^2	400,000 lb/in^2 28,100 kg/cm^2
Specific Tensile Strength	7.7 X 10^6 in. 19.5 X 10^6 cm	7.7 X 10^6 in. 19.5 X 10^6 cm
Modulus	12 X 10^6 lb/in^2** 0.9 X 10^6 kg/cm^2	19 X 10^6 lb/in^2** 1.34 X 10^6 kg/cm^2
Specific Modulus	2.3 X 10^8 in.** 5.8 X 10^8 cm	3.6 X 10^8 in.** 9.1 X 10^8 cm

*Trademark for Du Pont's aramid yarn.
**Modulus of Single filaments or ASTM D2343 Resin Impregnated Strand.
Source No. 1

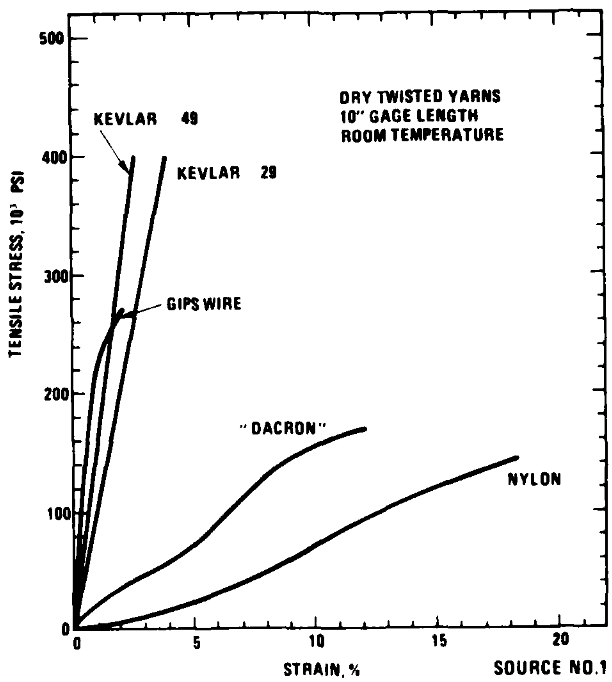

Figure 1-2 — Stress-Strain relation of various materials

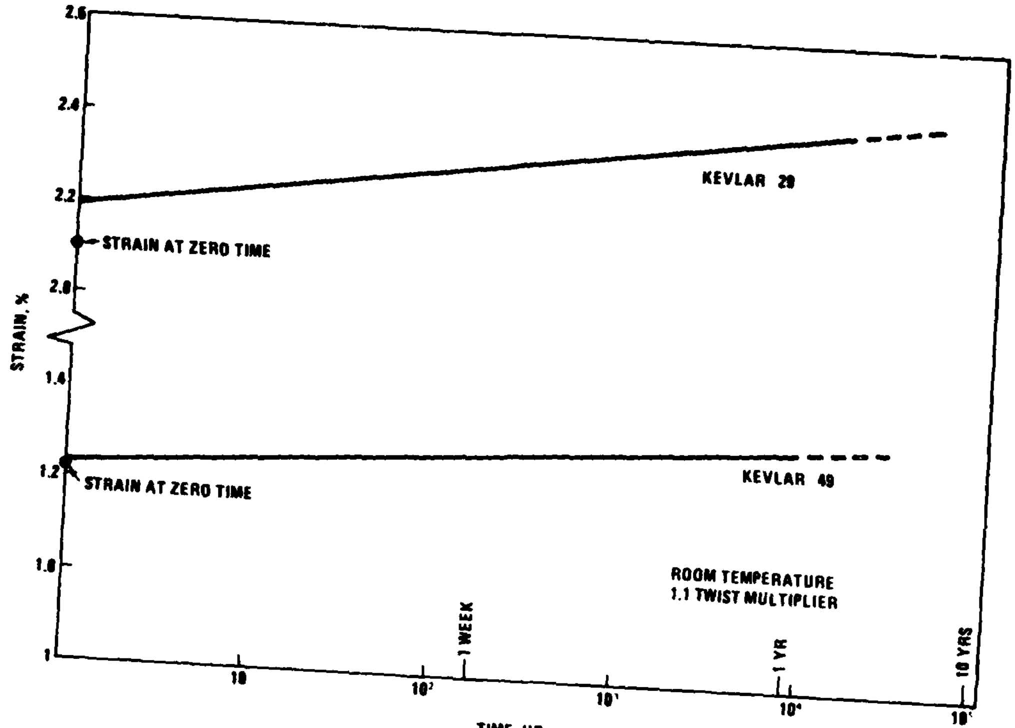

Figure 1-3 — Creep of Kevlar 29 and Kevlar 49 aramid yarns at 50% of ultimate strength

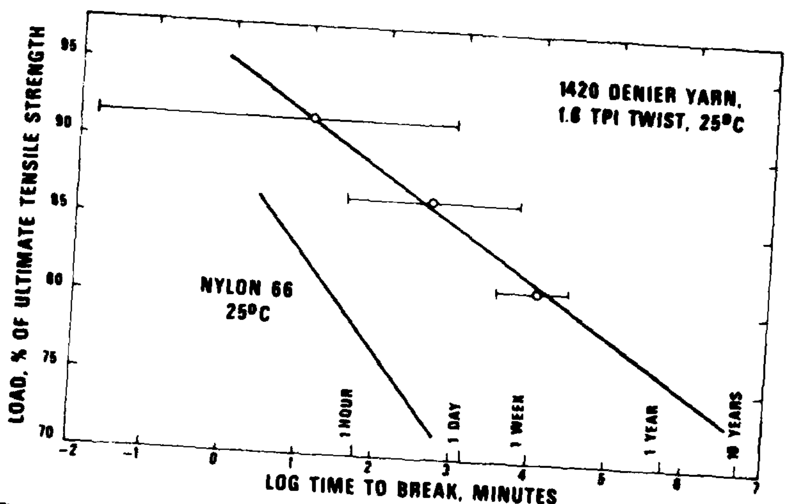

Figure 1-4 — Stress-rupture of Kevlar 49 yarn: time to failure under continuous static load

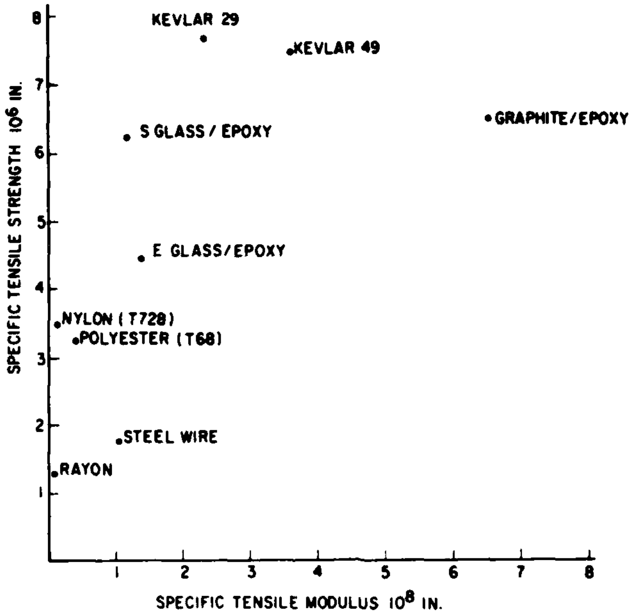

Figure 1-5 — Values of specific tensile strength versus specific tensile modulus for oceanographic strength member materials

1-3-2. Fatigue and Abrasion. The aramid fibers 29 have inherently good fatigue properties as shown by the relatively few test results available cited in Table 1-3.[7] Figure 1-6 compares the tension-tension fatigue properties of Kevlar to steel and nylon. At 10^7 cycles it will withstand 1.7 times the stress of steel and 3.4 times the stress of nylon. Earlier tests ascribed low fatigue values to the bare yarn; however, the real culprit was self-abrasion. The filament has a hard surface which can be removed by friction. In some fatigue tests, the filaments may abrade one another, which can cause early failure. Microscopic observation of the damaged ends can easily distinguish the difference between abrasion and fatigue failures. The self-abrasion resistance of aramid yarns is much poorer than that of nylon or polyester, although the finishes that are available help to reduce abrasion to some extent. A partial solution to this problem is to encapsulate or impregnate the yarns with a low-modulus material such as a polyurethane. This can be especially effective under dry conditions, but wet abrasion of impregnated strands and yarns is usually much poorer than dry. The abrasion resistance of impregnated strands can be improved significantly by applying a 3 to 6 percent overlay of wax, such as paraffin, on the impregnated strands, bringing the self-abrasion resistance to levels above nylon and polyester yarns. A slight twist ($\approx$1 twist multiplier) in yarn prior to resin impregnation also can yield significant improvements in abrasion resistance.

With unimpregnated yarns, self-abrasion resistance superior to nylon and polyester can be achieved through a combination of slight yarn twist (see section 1-2, Fig. 1-1) and the application of 15 to 20 percent of a resin-bonded solid lubricant such as Molykote Spray Lubricant (MoS_2, Dow Corning) or Dag 35 (graphite, Acheson Colloids, Inc.). Improvements in internal and external abrasion resistance of fabricated ropes can also be achieved by imbibing the ropes with resin-bonded solid lubricants or with various waxes such as paraffin or microcrystalline waxes.

[7] Ibid.

Table 1-2 — Comparison of Yarn, Filament, and Wire Nominal Properties

Material	Tensile Strength (psi × 10^3)	Elastic Modulus (psi × 10^6)	Elongation at Rupture (%)	Density (lb/in^3) (gm/cm^3)	Specific Tensile Strength 10^6 (in)	Specific Modulus 10^8 (in)	Dielectric Constant	Melting Point °F(°C)
Kevlar 29**	400	9	4.0	0.052 1.44	7.7	1.73	3.4	800 (430) (Chars)
Kevlar 49**	400	16.0	2.4	0.052 1.44	7.7	3.08	3.4	800 (430) (Chars)
Steel Wire	300	29.0	1.1	0.285 7.86	1.8	1.02	— —	2250 (1400)
Dacron Polyester Type 68**	168	2.0	15.0	0.050 1.38	3.2	0.40	—	480
Nylon Type 728**	143	0.73	19.0	0.041 1.14	3.5	0.12	—	450 (232)
Rayon** Viscose**	70	0.4	17.0	0.055 1.52	1.3	0.07	—	(Chars)
S Glass*	400	12.4	3.1	0.09 2.50	4.4	1.38	4.5	1540 (840)
E Glass*	575	10.5	3.1	0.092 2.55	6.3	1.14	4.5	1290 (700)
H S Graphite*	350	35.0	1.9	0.054 1.50	6.5	6.48	5.0	6600 (3650)

*ASTM D2343 (Resin Impregnated)
**Twisted Yarn Properties

Table 1-3 — Tension-Tension Fatigue of Kevlar 29 Yarns

Construction	Cycled Between % of Ult. Tensile Strength		Cycles	% Strength Loss
	Low	High		
1500 Denier/ 2 Ply Cords	45	74	1000	0
2 Ply Cords	29	52	1000	0
2 Ply Cords	8	31	1000	0
1500 Denier Yarn	0	10	13 × 10^6	5

Source No. 1

1-3-3. **Environmental Stability.** The aramid fibers have good chemical resistance to common solvents, oils, greases, and water. Table 1-4 shows how aramid reacts to a wide variety of chemicals, indicating that strong mineral acids and concentrated bases will degrade the yarn.[8] The uncoated fiber absorbs water from immersion or from a humid atmosphere. Kevlar 29 will pick up about 6 percent moisture by weight, and Kevlar 49 will pick up about 3 percent at 72°F and 55 percent RH.[9] There has been no indication that this in any way affects the properties of the material. Du Pont has noted that specimens submerged in the ocean for years show little loss in strength or modulus. However tests are presently underway at the Naval Research Laboratory (NRL) to verify this.

A series of creep tests were conducted to determine if long-term immersion of the fiber in water, while under constant tension, had any deleterious effects. The experiments were conducted on both the fiber as received from Du Pont (Kevlar 29) and the same fiber as impregnated with polyurethene. The results, shown in Table 1-5, show a small reduction in strength.

There is some strength loss due to hydrolysis when the material is exposed to high temperature and moisture, such as saturated steam.

Kevlar fibers have little shrinkage with increasing temperature. The longitudinal coefficient of thermal expansion is -2×10^{-6} in./in./°C. As the temperature increases, both the tensile strength and the modulus decrease. Figures 1-7 and 1-8 show short-term effects of rising temperature on various yarns.[10] Short exposures to temperatures as high as a 350°F epoxy cure cycle cause no discernible changes in tensile properties, but over long periods oxidation effects do take place which slowly degenerate the material. This is

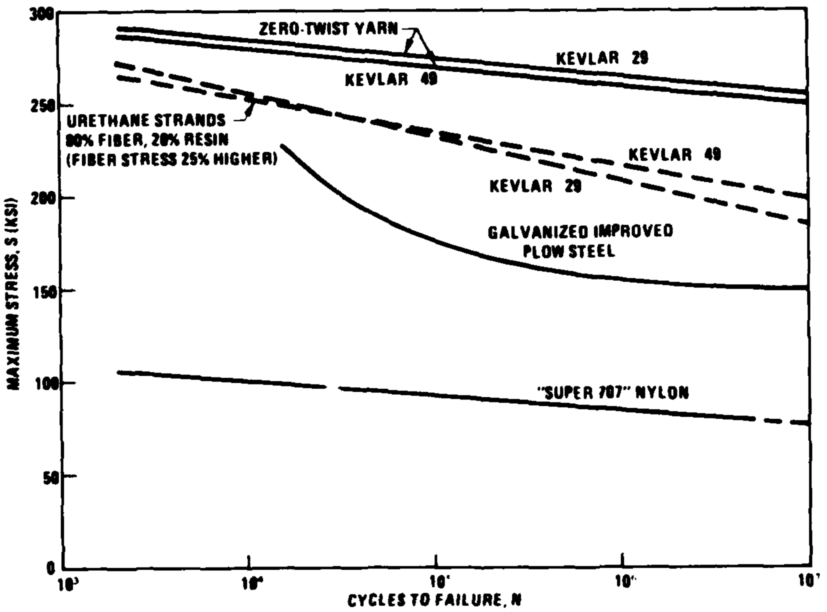

Figure 1-6 — Comparative tension-tension fatigue data SOURCE NO.1

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[8] Ibid.
[9] Ibid.
[10] Ibid.

Table 1-4 — Stability of Kevlar 29 and Kevlar 49 in Chemicals

Chemical	Conc. (%)	Temp. (°F)	Time (hr)	Strength Loss (%)	
				Kevlar 29	Kevlar 49
Hydrochloric Acid	37	70	24	—*	0
Hydrochloric Acid	37	70	1000	83	—
Hydrofluoric Acid	10	70	100	12	8
Nitric Acid	1	70	100	18	5
Sulfuric Acid	10	70	100	14	—
Sulfuric Acid	10	70	1000	—	31
Sodium Hydroxide	50	70	24	—	10
Ammonium Hydroxide	28	70	1000	10	—
Acetone	100	70	24	0	0
Dimethyl Formamide	100	70	24	—	0
Methyl Ethyl Ketone	100	70	24	—	0
Trichloroethylene	100	70	24	—	1.5
Trichloroethylene	100	190	387	7	—
Ethyl Alcohol	100	70	24	0	0
Jet Fuel (JP-4)	100	70	300	0	4.5
Jet Fuel (JP-4)	100	390	100	4	—
Brake Fluid	100	70	312	2	—
Brake Fluid	100	235	100	33	—
Transformer Oil (Texaco #55)	100	140	500	4.6	0
Kerosene	100	140	500	9.9	0
Freon 11	100	140	500	0	2.7
Freon 22	100	140	500	0	3.6
Tap Water	100	212	100	0	2
Sea Water (Ocean City, NJ)	100	—	1 Yr.	1.5	1.5
Water at 10,000 psi	100	70	720	0	—
Water-Superheated	100	280	40	9.3	—
Steam-Saturated	100	300	48	28	—

*Indicates data not available.

Source No. 1

Table 1-5 — Wet Creep Tests of Kevlar 29 Yarn

Sample	Load (%)	Terminal Break Strength (lb)	Modulus	Time Under Given Load (yr (days))
Raw	10	55.3	9.8×10^6	3.14 (1107)
	20	55.7	11.67×10^6	3.14 (1107)
	*30	37.8 (frayed samples)	7.7×10^6	2.68 (942)
	40	57.7	11.50×10^6	3.14 (1107)
	50	No data — failed destructively earlier this yr.		
Impregnated	10	62.7	9.40×10^6	2.95 (1039)
	20	62.7	10.22×10^6	2.95 (1039)
	*30	56	9.69×10^6	2.47 (872)
	*40	55.7	9.99×10^6	1.86 (656)
	*50	58.7	10.01×10^6	1.96 (692)

Break strength originally claimed for raw fiber B was 58.89 lb.
Break strength originally claimed for water-soaked fiber B was 58.175 lb.
Break strength and modulus values are an average of three samples.

*Samples had failed in the end fitting or nearby.

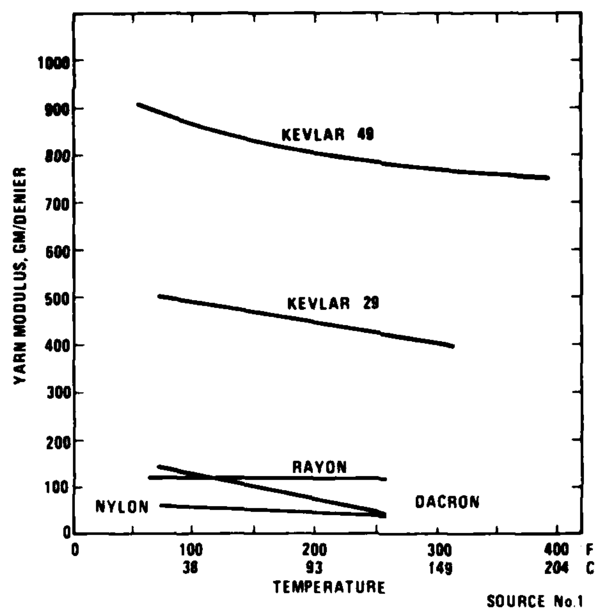

Figure 1-7 — Effect of temperature on yarn tensile modulus tested at temperature after 5-minute exposure in air

shown in Figure 1-9. Although both fibers are still useful above 400°F, long-term service above 300°F is not recommended. The material is inherently flame resistant and self-extinguishing. Moreover, it does not have a melting point, but chars and decomposes at 800°F.

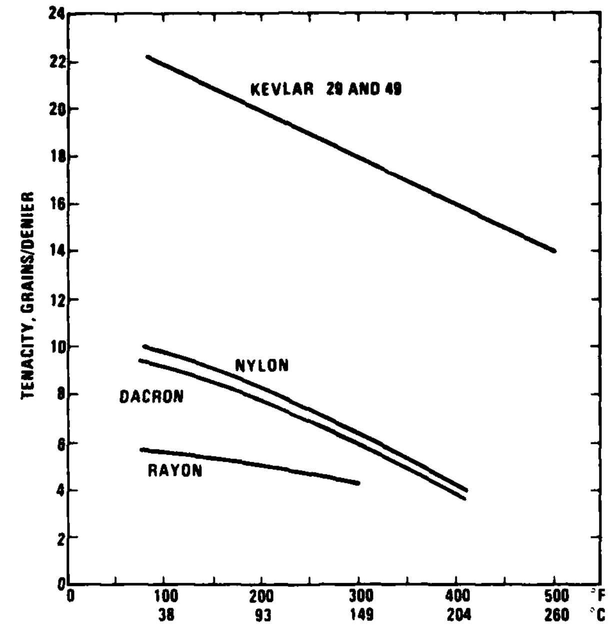

Figure 1-8 — Effect of temperature on yarn tensile strength tested at temperature after 5-minute exposure in air

In addition, tests were conducted on Kevlar 29 at -50°F to simulate Arctic conditions. The results given in Table 1-6[11] show that there are no natural environmental temperatures that would cause a problem with the use of Kevlar.

One climatic effect that must be noted is the aramid's sensitivity to the ultraviolet-radiation component of sunlight. This problem will be discussed in more detail later as it relates directly to ropes. It has been recommended that if this material is exposed to sunlight, it be shielded by a jacket of another material. Table 1-7 shows the percentage strength loss that can be expected from exposure of the bare yarn compared to a few aramid fiber ropes.

Finally, one must also take environmental pressure into account. In 1973, a number of Kevlar 29 urethane-impregnated strands were coiled and pressure-conditioned for one month at 10,000 psi. This was accomplished in four separate series of tests, the first three of which suffered some data-reduction problems. The fourth and final test supplied a good control series which, wher ompared with all the other test samples, showed a 12.1 percent reduction in tensile .rength.[12] More testing is needed in this area before the results can be considered conclusive. A series of pressurization tests have begun at NRL. The aramid fiber loaded at a percentage of its break strength is to be immersed in seawater and subjected to 8,000 psi for a total period of 3 months. The results will be reported as soon as possible.

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11 Ibid.
12 Letter Reports, "Kevlar 29" Composite Submergence Characterization Test, Oct. 1973 and March 1974, Philadelphia Resins Corporation Philadelphia, Pa.

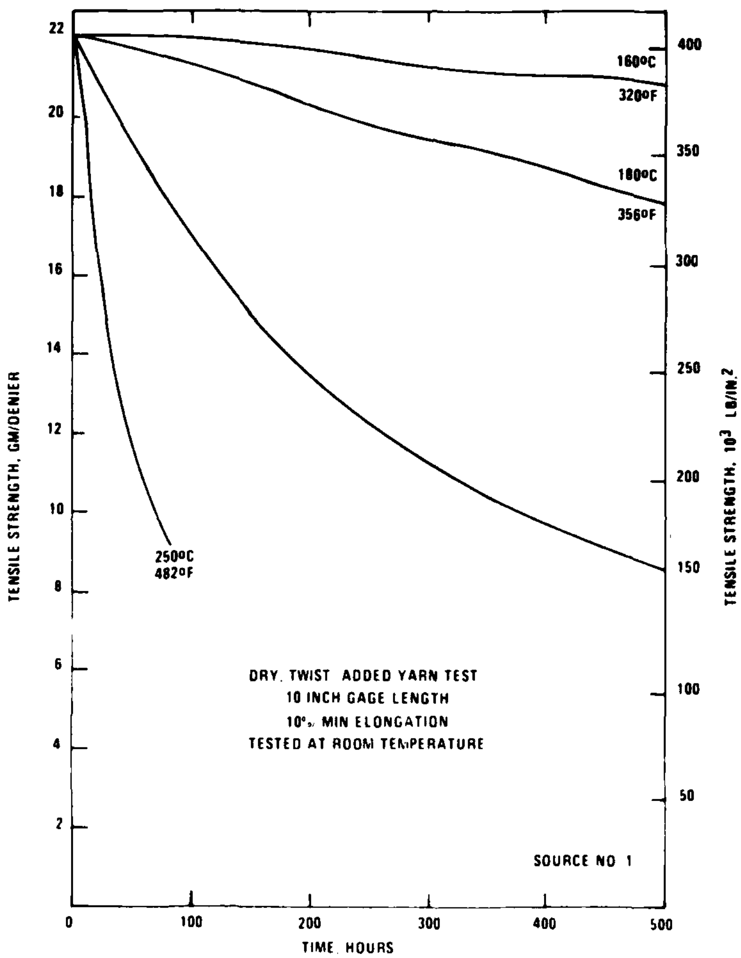

Figure 1-9 — The effect of temperature on the tensile strength of Kevlar 29

Table 1-6 — Tensile Properties of Kevlar 29 at Arctic Temperatures

Property	75°F	-50°F
Tenacity, GM/Denier	19.1	19.8
Tensile Strength, lb/in.^{2}	351,700	364,600
Elongation, %	4.1	3.9
Modulus, GM/Denier	425	521
Modulus, 10^6 lb/in.^{2}	7.82	9.59

Twisted Kevlar 29 Cord
6.5 Twist Multiplier
10%/Min. Elongation
10-in. Gage Length
Tested At Temperature

Source No. 1

Table 1-7 — Ultraviolet Stability of Kevlar 29 and Kevlar 49

Material	Size	Twist (tpi)	Exposure (hr)	Break Load, (lb) Before	Break Load, (lb) After	Strength Loss (%)
Kevlar 29	1500 den. Yarn (No Finish)	2.1	Weather-Ometer*, 200 Dry	72.9	53.5	27
Kevlar 49	1420 den. Yarn (No Finish)	1.8	200 Wet-Dry	71.4	53.3	25
			500 Wet-Dry		45.0	37
Kevlar 49	7100 den. Yarn (No Finish)	0.9	200 Wet-Dry	331	258	22
			500 Wet-Dry		220	34
Kevlar 49	7100 den.-Urethane Impreg.	0	200 Wet-Dry	344	228	34
			500 Wet-Dry		185	46
Kevlar 49	7100 den. Urethane Impreg.	0.9	200 Wet-Dry	356	285	20
			500 Wet-Dry		235	34
Kevlar 29 + 25% Dacron®	1/2-in.-dia. 3-Strand Rope		200 Dry	11,400	10,600	7
			Florida Exposure-Hialeah			
			6 Mo.	11,400	10,400	9
			12 Mo.		9,500	17
			24 Mo.		9,500	17
Kevlar 29	1/2-in.-dia. 3-Strand Rope		Florida Exposure-Hialeah			
			6 Mo.	14,400	13,000	10
			12 Mo.		11,600	19
			18 Mo.		9,950	31
			24 Mo.		9,940	31

*Weather-Ometer—Xenon Lamp
Source No. 1

CHAPTER 2. ARAMID FIBER MECHANICAL ROPES

2-1. CONSTRUCTION AND APPLICATION. A strength member's reaction to tensile forces depends on the combination of the material and the construction chosen. Therefore, the selection of a rope's structure is as important as the selection of its fiber. The proper arrangement of yarns can enhance some desirable fiber properties that are already present, and compensate some that are lacking.

Synthetic materials, in the form of singles yarns, can be used to construct three basic types of rope: twisted, braided, and parallel lay. As can be expected, there are numerous variations in each category. Table 2-1 lists some of the more common types.

Table 2-1 — General Types of Ropes

Types of Rope	Variations
Twisted	Three Strand Four Strand Cable Design Double Helical Lay
Braided	Solid Braid Single Braid Double Braid Plaited
Parallel	Parallel Strand Parallel Yarn

2-1-1. Twisted Ropes. Before the development of today's continuous-length synthetic fibers, ropes could be constructed only by twisting short lengths of natural fibers together. This intertwisting served two purposes: first, it held the rope structure together; second, it allowed the structure to transfer a tensile load through interfilament friction. In most cases, the yarns are twisted into plied yarns, the plied yarns into strands, and the strands into ropes. There are two distinct drawbacks to this approach. A torque is generated under tension, and the rope can have a low strength conversion efficiency.

As a tensile load is applied to a twisted rope, the individual components attempt to straighten, thereby inducing a torque. If one end of the loaded rope is free to turn, the lay of the rope lengthens as it revolves, reducing the torque to zero. Upon the sudden release of the load, a torque is induced in a direction against the lay. With no tensile

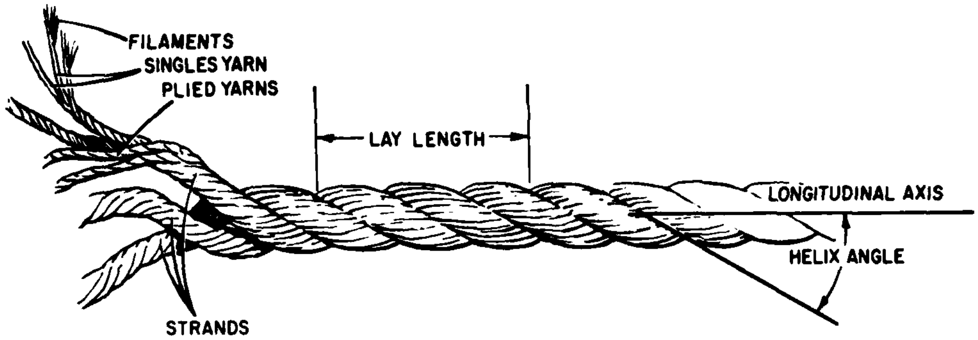

Figure 2-1 — 3 strand twisted rope

forces to keep the strands in place, they can immediately form kinks or hockles.[1] Therefore, caution is required when stranded, twisted ropes are to be used with a free end, such as in lowering anchors or in mooring buoys. Moreover, improper handling of a stranded rope can impart a twist opposite to the lay, which invariably causes hockles. For instance, care must be taken that turns are not wound onto a capstan or gypsy head opposite the direction of rope lay.

The strength conversion efficiency of any twisted rope is a function of its helix angle. The maximum strength of a continuous filament is obtained by laying all the fibers parallel. But since this imposes other restrictions which are unacceptable for some uses, the reduction in strength can be a necessary design concession. This loss can be quantified by expressing it as the percent conversion efficiency of the rope. The conversion efficiency is equal to the rope tenacity divided by the yarn tenacity when multiplied by 100. The percent of tensile strength lost due to twist is determined largely by the magnitude of the helix angle of the strands. The lay of a strand follows a helical path around the rope. The angle of this path with respect to the longitudinal axis of the rope is the helix angle (see Figure 2-1).

The bare aramid fiber does not lend itself well to twisted rope. This is due to the fact that the fibers are easily abraded by each other and by any other object they might rub against. Impregnation or, to a lesser extent, the Du Pont applied cordage finish, can reduce the internal self-abrasion tendency of the fibers, and the coating or a jacket can reduce external abrasion and mechanical damage.

The tensile strength of cable-designed Kevlar aramid fiber ropes compares favorably with that of steel wire ropes. But, as with all Kevlar ropes, care must be taken with respect to abrasion and cutting resistance. If this is not a consideration in the selection process or if jackets can afford the needed protection, the more expensive aramid rope has the advantages of low weight, long tension or fatigue life, ease of handling, and lack of corrosion problems.

The construction of the cable-designed rope is designated by two figures just as wire rope is. The first figure gives the number of strands in the rope; the second figure gives the

[1] Rosenthal, Felix, "Greenhill's Formula and the Mechanics of Cable Hockling," NRL Report 7940, Naval Research Laboratory, Washington, D.C., Nov. 7, 1975.

Table 2-2 — Average Values of Some Presently Available Cable-Design Twisted Aramid Fiber Ropes

Design	Nominal Diameter (in.)	Minimum Tensile Strength (psi)	Approx. Weight of Bare Rope (lb/1000 ft)
1 X 7	0.127	2,100	6
1 X 19	0.127	1,800	5.5
1 X 19	0.196	4,500	13.5
7 X 7	0.195	4,000	14
7 X 7	0.425	15,000	49
19 X 7	0.45	17,500	48
19 X 7	0.51	22,000	72
6 X 19-IPC	0.58	30,000	95

Source No. 2

number of yarns or ends in the strand. An example would be a 19 X 7 configuration which has 19 strands with 7 ends in each strand. At equal diameter, the more strands in a rope, the more flexible it is. Table 2-2[2] lists the cable-designed aramid fiber ropes available from one company along with each cable's minimum break strength and weight. Table 2-3 compares different cable materials of similar construction.

2-1-2. Braided Ropes. A braided rope is constructed by interlacing an equal number of yarns or strands. The rope is prevented from unlaying by the interlocking weave. The yarns twisted to the right are balanced by the same number of yarns twisted to the left, allowing the structure to be torque free. Normally, braided rope has greater strength and lower elongation than a three-strand rope of equal diameter. However, because the impregnated Kevlar is stiff, it requires a reduced helix angle and a more open weave. Thus, the fibers are more nearly parallel and suffer less transverse stress. An additional advantage is the fact that braided ropes have a round, smooth exterior which tends to flatten out on a bearing surface. The wear is distributed over a large area. Hence, the rope's abrasion resistance is increased.

Braided rope construction can be designated by a large number of interrelated specifications, some of which are illustrated in Figure 2-2. By increasing either the braid angle (α) or the crimp angle (θ), both the rope modulus and the rope strength are reduced. For example, a braided rope with an α of 30° and a θ of 20° has a calculated 68 percent of the strength of a rope with the same strands laid parallel and only 30 percent of the

[2] "Phillystran," Philadelphia Resins Corporation Bulletin No. 113, January 1975.

Table 2-3 — Comparison of Various Cable Materials with Similar Constructions

Construction	Nominal Diameter (in.)	Material	Break Strength (lb)	Approx. Wt. of Bare Rope (lb/1000 ft)		Approx. Cost ($/1000 ft)
				In Air	In Water	
1 X 7	1/8	Aramid*	2,100	6	2	150
		---------	-------	-	-	-
		Galvanized (Extra High Strength)	1,830	32	28	60
1 X 19	3/16	Aramid*	4,500	13.5	4	350
		Stainless Steel	4,700	77	67	380
		Carbon Steel Aircraft	4,700	77	67	80
7 X 7	1/4	Aramid*	6,000	21	7	650
		Stainless Steel	6,100	106	93	750
		Galvanized	6,100	106	93	250
6 X 19	1/2	Aramid (IPC)*	30,000	95	29	2,250
		Stainless Steel	22,800	460	400	
		Galvanized (Extra Improved Plow Steel)	26,600	460	400	400

*Kevlar Fiber Phillystran
IPC — Independent aramid fiber core
IWRC — Independent wire rope core

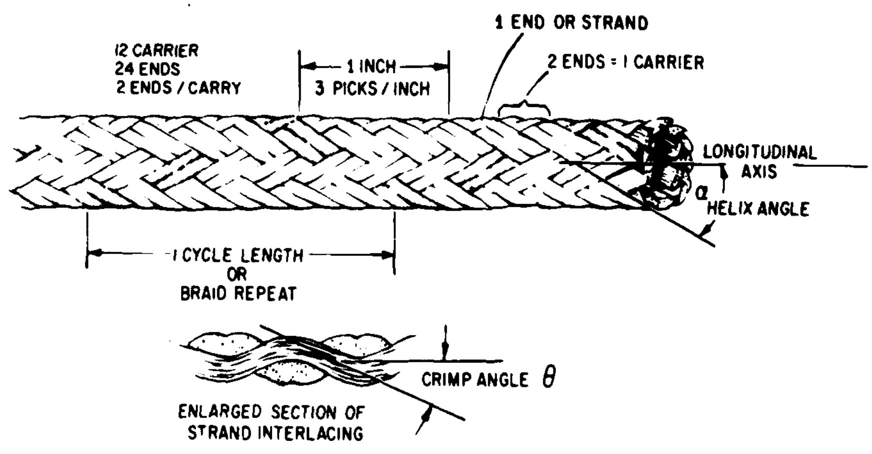

FIGURE 2-2 TUBULAR DIAMOND BRAID

parallel strand modulus.[3] The use of more strands or ends per carrier has some definite advantage; namely, (1) smaller strands can be used, (2) core popout is minimized, and (3) a slightly better modulus and strength can be realized for the same angles.

Braided ropes come in a number of constructions. The single or hollow braid is not really hollow when under tension. However, it does have a tendency to flatten out as the number of strands increases.

Double braids are constructed of two braid ropes, one inside the other. The inner is called the core; the outer is called the cover. Properly fabricated, they share the load equally. Although the inner and outer ropes are usually of similar material, they can be made up of two different materials. By balancing the various braid geometry factors, a rope could utilize the optimum properties of each fiber. For example the core could be an impregnated aramid fiber for maximum strength, and the cover could be nylon or polyester for maximum abrasion resistance.

Again, as in the case of twisted ropes, impregnation of the aramid yarns with a low-modulus material such as polyurethane can reduce abrasion and increase the life of the rope. Where cyclic loading over a sheave is not a problem, the unimpregnated fibers can be used at lower cost. Many types of aramid fiber braids are currently available: tubular, solid, plaited, braid over a core, single braid, and double braid. One particular combination consists of an aramid stranded cable-design rope over which additional layers of aramid yarn are braided. The number of braided layers added depends on the required break strength. A final jacketing of black polyurethane is extruded over the rope to improve external abrasion resistance.

As the tension on a braided rope increases, the braid spacing becomes closer, exerting a compressive force directed toward the center of the rope. As the diameter of the rope increases at some point depending on the braid geometry, the internal compression forces of a series of braids over braids could exceed the transverse strength of the material. The radial pressure generated on the core is given by the equation

$$P_R = \frac{FM \sin^2 \alpha}{2\pi R^2 \cos \alpha},$$

where P_R = radial pressure, F = effective tension in a given strand, M = number of strands, R = radius, and α = helix angle[4] Braided ropes have been designed with elastic cores to minimize the problem.

The principal merits of braid are:

(a) Self-limitation of the effects of strand damage. Local imperfections and individual strand damage are averaged over a short length of the cable. Even if each strand is cut many times along the length of the cable, only a slight decrease in cable strength will result as long as the cuts are separated by several feet.

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[3]"Analysis of the Mechanical Behavior of a Kevlar 49 Tubular Braided-Sleeve/Core Electromechanical Cable," Naval Underwater Systems Center Technical Report, 15 May 1974, Newport, Rhode Island.
[4]Ibid.

Table 2-4 — Strength of Small Tubular Braided Kevlar 29 Ropes

Number of Ends in Rope	Denier of Ends	Diameter of Rope (in.)	Break Strength of Rope (lb)	Weight (lb/1000 ft)
8	200	0.025	50	0.13
8	400	0.025	100	0.27
8	1000	0.030	300	0.6
10	1000	0.035	400	0.8
4	1500	0.042	200	0.5
8	1500	0.060	400	1.0
12	1500	0.060	600	1.4

Source No. 5

(b) Ease of end fitting with eye splices, epoxy-potted conical sockets, or braided grips.

(c) A wide range of strengths through choice of strand sizing, braid design, and number of layers.

(d) Excellent cyclic-tension fatigue life at high stress levels.

(e) Low elastic stretch.

(f) Flexibility and small bending radii.

(g) Excellent cost effectiveness, within certain ranges, in relationship to alternative materials and strength requirements.

(h) Ease of fabrication, which requires considerably less precision than alternative constructions.

(i) Complete torque balance.

The aramid braid's principal fault is that it is susceptible to failure by abrasion when cycled over pulleys, both by interfiber and surface abrasion. Advances by Du Pont, described in Section 1-3-2, should alleviate this problem considerably. Table 2-4 lists some typical break strengths of small braided ropes.

2-1-3. Parallel-Fiber Rope. With the introduction of the continuous-filament synthetic fiber a new design in rope structure was made possible. The yarns could be laid parallel to each other, allowing an increase in break strength by orienting all the fiber in the direction of the rope axis. For a given diameter rope, cycled in tension-tension, the parallel lay construction offers maximum strength and minimum elongation. If properly constructed, the strength of this rope is close to the aggregate strength of all the individual yarns. There is minimum constructional elongation; the stretch of the rope is primarily due to the material stretch. Moreover, internal abrasion is reduced.

To obtain the maximum benefit from all these advantages, care must be exercised in the manufacturing process. Due to the facts that the material's modulus is so high and that there is no material-yielding before rupture, an aramid parallel-fiber rope must be constructed so that all the individual strands share the load equally. Uniform pretensioning and careful alignment of the strands are two major factors in accomplishing this. Otherwise, the shortest yarn or strand will be the first to take up the load. A strand ruptures, passing the load to another strand, then another, until the rope has failed at a load lower than the theoretical strength.

Because there is no interlocking structure, the rope must be jacketed. This reduces the strength-to-weight ratio in air over the bare yarns, but, if the jacket material has positive buoyancy, it could increase the ratio in water. The jacket is also an asset where abrasion resistance is a concern. As with the braided ropes, there is no torque; hence there are no problem with kinks or hockles due to tension relaxation.

However, as with other structures, there are design tradeoffs. First, depending on the jacketing material and the fiber impregnation, the parallel lay can be more rigid than other constructions. This need not necessarily be so, however. Proper material selection can produce a flexible rope.

Second, parallel lay rope is not recommended for use as working or running rigging over small bending diameters. In twisted or braided ropes, the yarn's helical path insures equal fiber-stressing as the rope rounds a sheave or capstan. When parallel lay ropes are bent, the center fibers are stressed at a median load level. While the fibers on the inner side of the curve, against the sheave or drum, are stressed at a lower-than-median level (in compression, for example), the fibers on the outer side of the bend are carrying most of the load. The recommended bending radii for ordinary applications are roughly 24 times the rope diameter[5] (i.e., sheave diameters should be 48 times the rope diameter). If the rope is to be cycled, higher ratios should be used. For low loads or cycles, the ratio can be reduced. Kevlar is well-suited to the parallel-lay rope. The internal abrasion problem inherent with the aramid fiber is minimized. The jacketing material, necessary to the structure, provides external abrasion resistance. In this respect, it is still a fiber and cannot match the abrasion resistance of steel.

Last, this construction makes maximum use of the fiber's great tensile strength and its low elongation, which are the two outstanding characteristics of the material. Used in standing rigging such as guy wires or mooring lines, its life and service should be excellent.

2-2. ARAMID FIBER ROPE MECHANICAL PROPERTIES

2-2-1. Static Properties. Most rope selection begins with values taken from a load-elongation curve. However, other static tests include creep and stress rupture data. The following paragraphs contain a discussion of those static mechanical properties pertinent to the designer.

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[5] "Uniline" Bulletin No. UN-100, Wall Rope Works, Beverly, N.J.

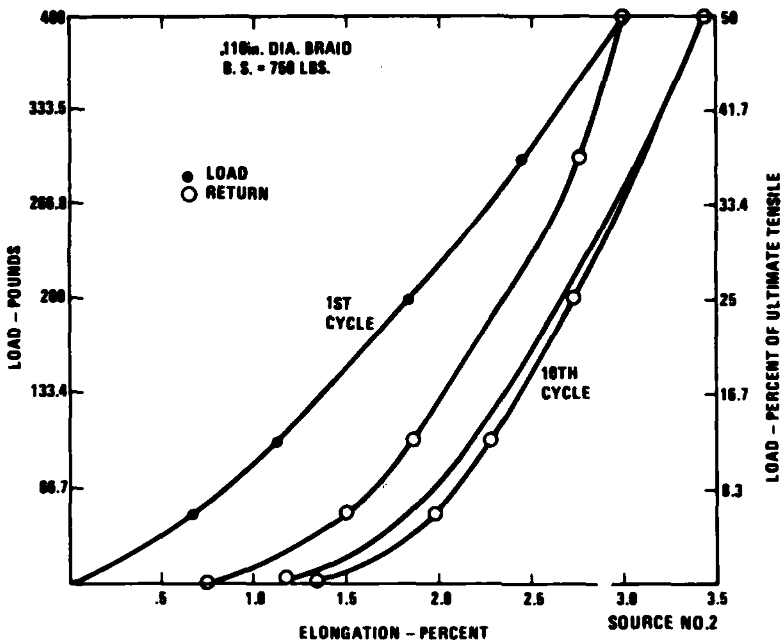


Figure 2-3 — Typical load elongation curve of a braided rope

2-2-1-1. **Load Elongation.** Information on the break strength and the elongation at rupture of Kevlar aramid fiber ropes is readily available from a number of manufacturers. Due to the many variables of rope design and construction techniques already discussed in section 2-1, it is best to obtain the information directly from the companies concerned. Figures 2-3, 2-4, and 2-5 are discussed in the following paragraphs only to present some ideas on the load elongation relationship of the various rope construction.

Figure 2-3 shows typical load-elongation curves of a Kevlar 29 braided rope with a diameter of 0.110 in. and a tensile strength of 750 pounds.[6] The curve shows the first cycle loading to 50 percent of break strength. The rope elongates about 3 percent, of which 0.75 percent is constructional stretch. On the tenth cycle the elastic elongation is only about 2.3 percent. But, at this point the constructional stretch has been reduced to roughly 0.3 percent.

Figure 2-4 shows the load elongation curves of a 3 by 7 cable-designed rope.[7] The first cycle loading has 2.95 percent total elongation of which about 1.30 percent is constructional. By the tenth cycle, constructional elongation is almost eliminated. As previously mentioned, both the constructional and elastic elongation will depend to a large extent on the constructional parameters of the rope.

Figure 2-5 contains two load-elongation curves for a parallel-lay rope.[8] The first is the initial loading; the second curve shows the load-elongation relationship many cycles later. During normal usage, the load elongation record of a parallel-lay rope would lie between

[6] "Elongation of Phillystran Cables," Philadelphia Resins Corporation, April 24, 1974.
[7] Ibid.
[8] Hood, H. A., "A New Look in Rope Making. The Parallel Yarn Approach," Wall Rope Works, Beverly, N.J., July 1975.

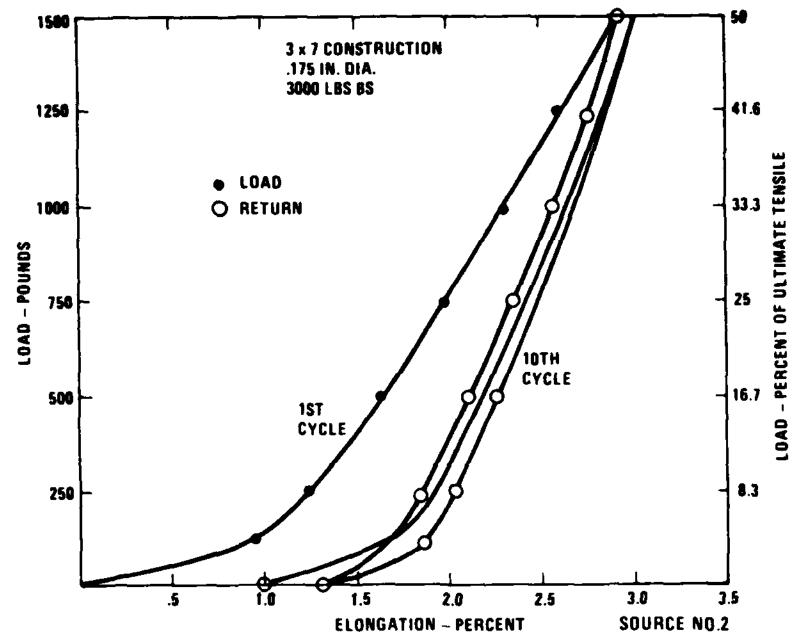


Figure 2-4 — Typical load elongation curves of a cable design rope

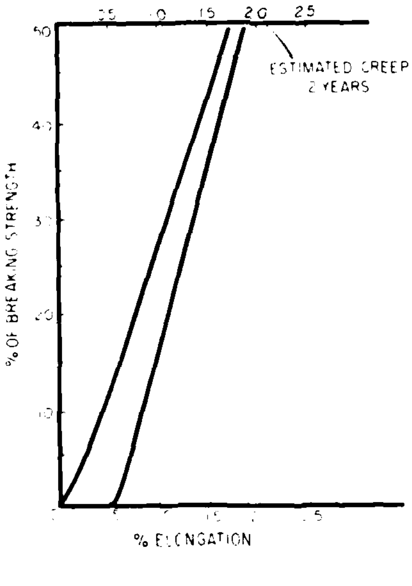


Figure 2-5 — Typical load elongation curve of a parallel-lay rope

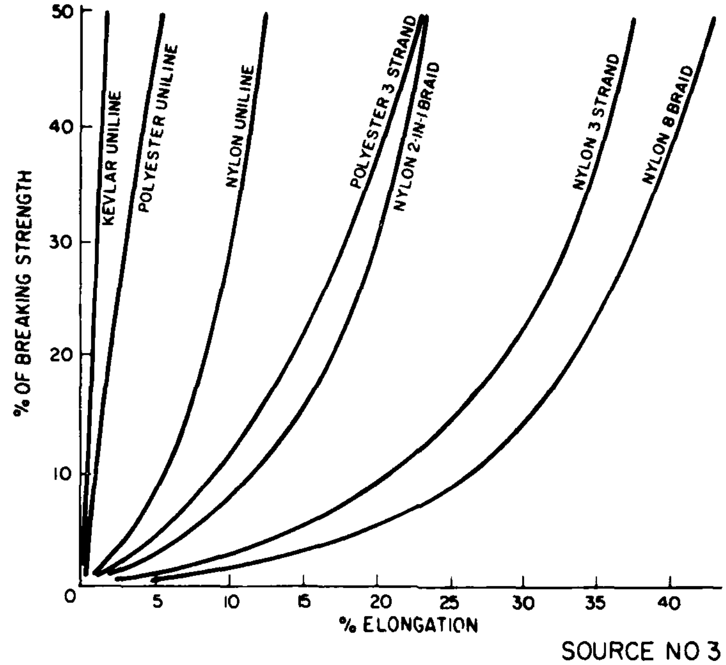


Figure 2-6 — Comparative first load/elongation curves

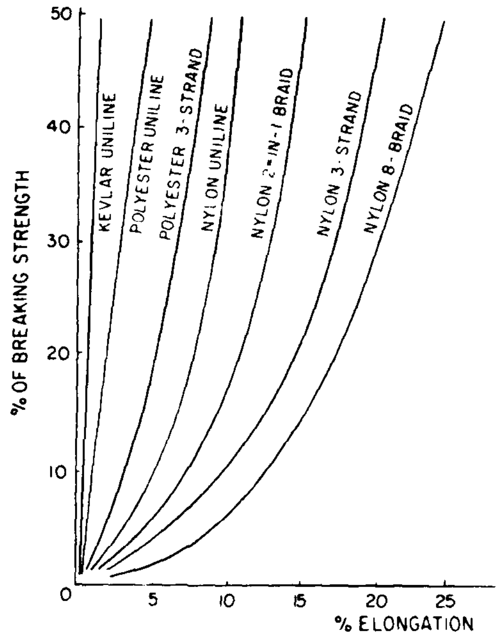
the two lines. Infrequent use and/or low loads should place the curve near the left slope. Frequent use and/or high loads would tend to move the curve to the right. The constructional stretch found in twisted and braided ropes is almost nonexistent in the parallel lay. Also, the elastic stretch is the smallest of the three types of rope at the start, and it does not drop off as rapidly after prolonged use. Figures 2-6 and 2-7 compare the elongations of various synthetic materials and different constructions.[9] All the tests mentioned in this section have been conducted in air.

2-2-1-2. Creep. Creep is the name given to the nonrecoverable elongation of a material which is held under sustained loading. Its magnitude is a function of the load and the length of time the load is maintained. After removal of the stress, the material usually exhibits some elastic recoverable stretch and some permanent deformation.

Aramid fibers possess very low creep after a small initial elongation, as shown in Figure 1-4. Figure 2-8 shows the results of creep tests on polyurethane-impregnated Kevlar 29 aramid fibers (1,500-denier yarn).[10] The sets of tests were performed, one in air and one in water. Variations between the two sets are probably due to test procedures and apparatus and not to actual material differences. However, they do show that creep is not a significant problem. Creep is load dependent (within tested range) and results in less than 0.2 percent elongation per year for the first year. Figure 2-9 compares the various synthetic ropes for which data are available. The curves on nylon came from

[9] "Study of Creep Characteristics of Phillystran, 29" Philadelphia Resins Corporation, Montgomeryville, Pa.

[10] Swenson, R.C., "The Cable Development Program for Suspended Sensor Applications," NUSC Technical Report 4915, Naval Underwater Systems Center, New London, Conn., 1975.



SOURCE NO. 3

Figure 2-7 — Comparative elastic stretch after cycle loading

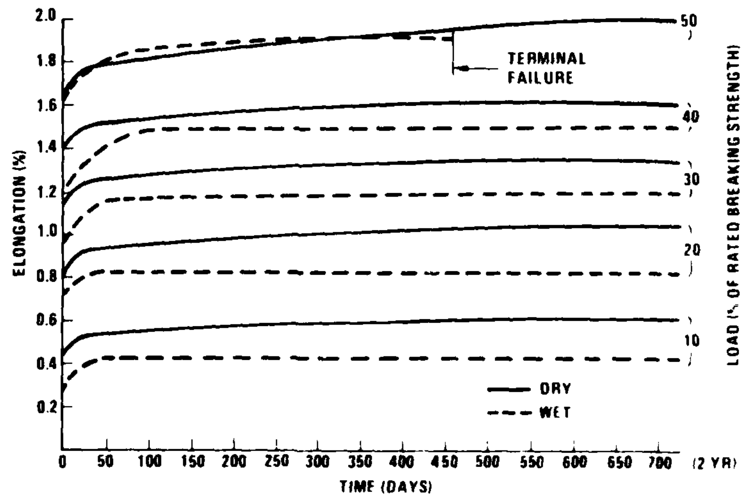


Figure 2-8 — Results of creep measurements for Kevlar fiber (1,500-denier yarn)

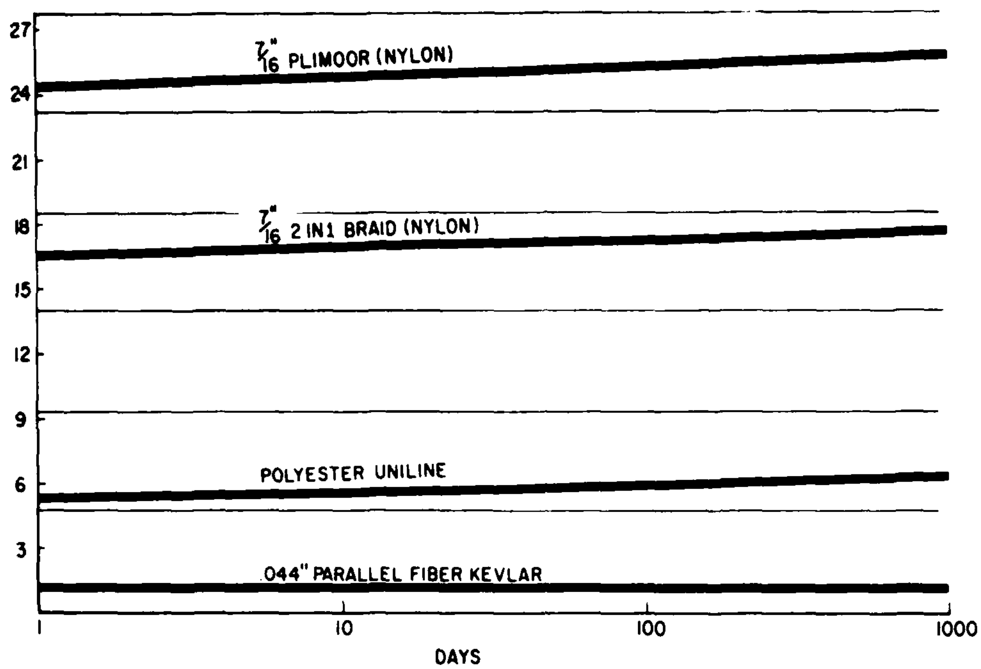


Figure 2-9 — Creep of various ropes loaded to 30 percent of break strength

Flessner's report on creep,[11] and the polyester information was taken from a French paper.[12]

2-2-1-3. Static Fatigue. As creep is related to elongation under load, static fatigue is related to creep. Static fatigue or stress rupture tests are conducted in much the same way as the long time creep tests discussed previously. A constant load is applied to a specimen at a constant temperature. However, because the load is now at a very high percentage of the break strength, the time to break the specimen is recorded rather than the elongation.

Tests conducted at various laboratories have shown that many specimens of aramid fiber stressed under relatively high loads (> 70 percent) have failed suddenly after varying time periods. Data points taken by the Naval Air Development Center[13] show that at loads above 70 percent of break strength, failures occurred at mid-span within a time range of a few seconds to several days. Only samples without overstressed points, loaded below 70 percent, have been suspended for long periods without failure. However, reference to Figure 1-4, published by Du Pont, and to a paper on the stress rupture behavior of Kevlar 49 aramid fiber indicate that Kevlar, on the average, is not as unstable above 70 percent as it might first appear.[14] Moreover, considerable scatter exists in times to

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[11] Flessner, M.F., "Creep Tests on Synthetic Mooring Lines," U.S. Coast Guard Academy, May 6, 1970.
[12] Report on Creep, Rhone-Poulene Textile, Paris, France, 1972.
[13] Brett, John P., Holler, Roger A., "Investigation of Kevlar Fiber Cables for Use in ASW Sonobuoys," Naval Air Development Center, Warminister, Pa., 20 Jan. 1975.
[14] Chiao, T.T., Rells, J.E., Moore, R.L., Hamstad, M.A., "Stress Rupture Behavior of Strands of An Organic Fiber/Epoxy Matrix," Lawrence Livermore Lab., ASTM, March 1973.

failure at high load. In addition, any nonuniformities in rope construction can lead to localized overloading and early failure at high loads. The conclusion can be drawn that static fatigue is a problem only near the upper load limit. The higher the applied load, the shorter the fiber life.

One manufacturer of Kevlar lines has put forth a series of conclusions based on various sources.[15] They are:

1. For sustained loads over 1,000 hours, one cannot safely operate over 70 percent of the tensile strength.
2. Each decrease of 5 percent of ultimate fiber stress increases the time to failure fivefold.
3. At 90 percent or greater of the ultimate tensile stress, the rupture will occur in less than 5 minutes.
4. In a tensile test at the conventional 0.005-in./in./min constant strain, a 10-in. gap length may never test over 90 percent of the calculated ultimate.
5. The percentage decrease for each order of magnitude in time would therefore have to be determined for the specific programmed load, the composite Kevlar/polymer used, and the design involved.

2-2-2. Dynamic Properties. Dynamic stresses can be induced in a rope by a number of forces: imposed and self-excited vibration, passage over sheaves, impulse loading, and tension cycling. The simple action of lowering a weight from a pitching, heaving, rolling ship can produce enough combined stresses to fatigue a rope beyond its break strength. Preliminary measurements indicate that Kevlar aramid fiber has excellent fatigue life.

2-2-2-1. *Cyclic-Tension Fatigue.* Tension-tension cycling induces fatigue in a rope by continual tensile loading and unloading. If an aramid rope were to be chosen for this task only, the parallel-fiber rope would minimize the possibility of internal abrasion. Since ropes are chosen for other purposes and only incidentally suffer cyclic loading, other types of ropes are covered.

A series of tests were performed on braided ropes of 2,100-pound break strength. The samples included two types of braid. One of each type was impregnated with urethane; the other made with cordage finish yarn. All the specimens were cycled to 800 pounds 20, 2,449, 7,503, and 15,000 times. The conclusions were that after 15,000 cycles the impregnated braid properly constructed loses little or no strength.[16] Tests have just been completed on a 19 X 7, 0.23-inch-diameter aramid fiber rope with a rated break strength of 6,000 pounds. It has been cycled to 40 percent of its break strength over 7 million times with no reduction in strength.[17] There is still more testing to be done, but at the present time it appears that tension-tension cycling has little effect on most Kevlar ropes.

2-2-2-2. Bending Fatigue. Cyclic fatigue testing of ropes over sheaves is a realistic method of predicting the life of running lines. Again, internal and external abrasion is the major problem, but it is a solvable one. Internal or self-abrasion can be reduced by impregnation, especially with the addition of wax overlays or by imbibing soft cordage with waxes

[15] Cortland Advanced Product Information Sheet No. 2B Nov. 1974.
[16] "Dynamic Comparison of Kevlar 29 Braid with Phillystran Braid," Philadelphia Resins Corp., Montgomeryville, Pa., May 31, 1974.
[17] Conversation with S. Whitehill, Philadelphia Resins Corporation.

Table 2-5 — Reverse Bend Cycling Test Results for Impregnated Braids and Wire Rope Constructions

Load = 20% Ultimate

Cable	Helix Angle (deg)	Load (lb)	D/d	Jacket, Yes or No	Other Conditions	Cycles to Failure
Impregnated Braids	14.6	1550	24	Yes		870
	14.6	1125	24	Yes		1284
	21.8	1450	24	Yes		1461
	21.8	1450	24	No		1686
	21.8	1450	24	No	11.4% Wax Overlay	66,375
	28.9	1300	24	Yes		5442
	28.9	1300	24	No	10.9% Wax Overlay	117,750
	36.6	1125	24	Yes		33,560
Unimpregnated Braids	≈12	20% UTS	24	No		396
	≈12	20% UTS	24	Yes		1320
	≈34	20% UTS	24	No		1296
	≈12	20% UTS	24	No	10-12% Wax Impreg.	13,000
Wire Rope Construction (19 X 7) Impregnated	15	1160	24	No		40,000
	15	1160	24	Yes		100,000
	15	1160	24	No	10-12% Wax Overlay	>400,000
Steel Wire Rope (19 X 7)	15	1200	24	No	Lubricated	50,000

Source No. 1

or resin-bonded solid lubricants as described earlier (Section 1-3-2). Jacketing the exterior of the rope with polyester, nylon, Dacron, or polyurethane increases the external abrasion resistance, thereby increasing the bending fatigue life. The most obvious method of improving bending-fatigue life is to maintain as large a sheave-to-rope diameter ratio (D/d) as possible. Data supplied by Du Pont on the reverse bend cycling of various ropes over pulleys (Table 2-5 and Figure 2-10) indicate that Kevlar ropes of wire rope construction are particularly effective in cycling life-time and that jacketing material can have an appreciable effect on the lifetime. For instance, a 19 X 7 urethane-impregnated Kevlar 29 rope cycled at 20 percent of ultimate over pulleys of D/d = 24/1 went 40M cycles to failure with no jacket, 100M cycles with an extruded urethane jacket, and 183M cycles to failure with a braided, Type 77 Dacron polyester jacket. A lubricated 19 X 7 steel cable, under the same conditions, went 50M cycles and failed in fatigue, while the Kevlar 29 cables failed via abrasion, including abrasion between the Kevlar and the sheave or between the Kevlar and the inside of the jacket. In figure 2-10 the D/d was held constant as the tension was varied, thereby varying the safety factor. The required D/d for working ropes will vary with rope construction, but it is recommended that a minimum factor of 24/1 be used with braided and with twisted ropes and 48/1 be used with parallel-lay ropes.

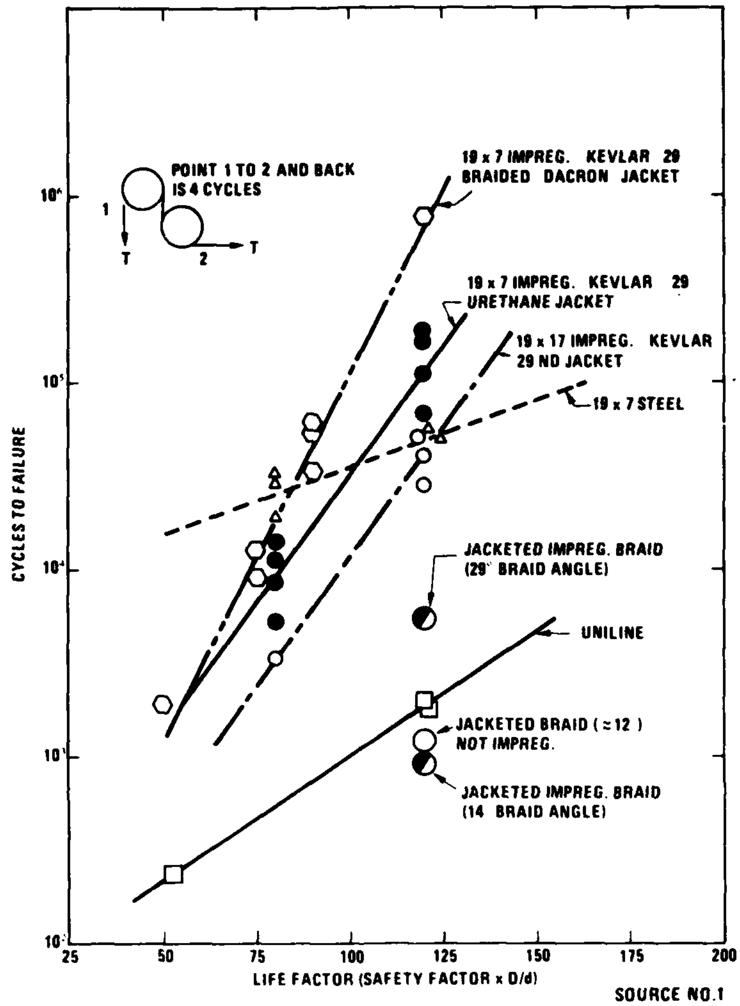

Figure 2-10 — Reverse bending performance of ropes

Unimpregnated and impregnated braids and ropes of Uniline construction gave poorer cyclic lifetime. The performance of impregnated braids showed a strong improvement with increasing braid angle, with a small decrease in ultimate break strength.

Table 2-5 also shows that a wax overlay on impregnated strands in braided and wire rope constructions and a wax imbibing of soft cordage braids yield improvements in cyclic lifetime over sheaves of 10-40X.

2-2-2-3. Cyclic Impact Tests. Cyclic impact tests determine how many times a rope will absorb a large amount of energy before it fatigues; it also is a good check on the durability of the rope's end fittings. Preformed Line Products ran such a test on a Kevlar Uniline rope and a 3/8-inch 3 X 19 construction galvanized improved plow steel cable.[18] The 3/8-inch aramid parallel-fiber rope with a break strength of 14,000 pounds survived

18 "Cyclic Impact Test of Kevlar and Steel Cables for Naval Underwater Systems Center," Preformed Line Products, Cleveland, Ohio, August 1975.

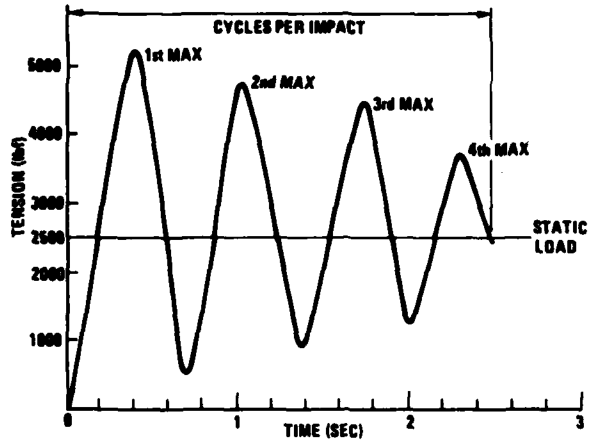

Figure 2-11 — Cable stress during cyclic impact testing of Kevlar mooring line (14,000-lb break strength)

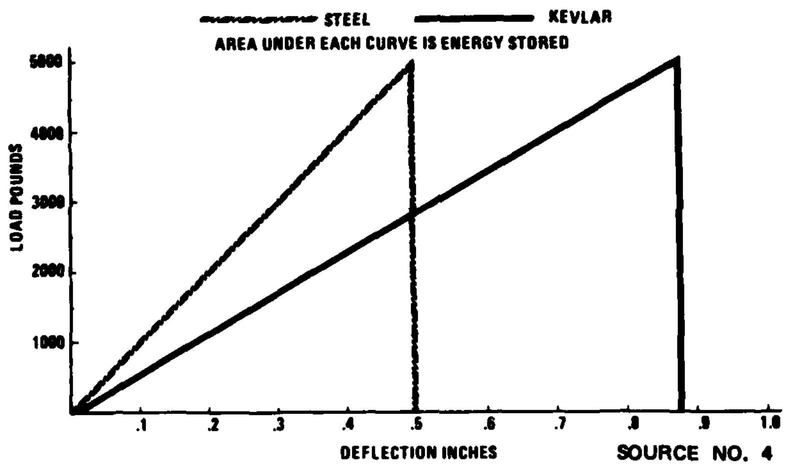

Figure 2-12 — Kevlar and steel energy stored at equal load

100,000 impacts or a total of 400,000 tension oscillations where the maximum load was 5,000 pounds. (Figure 2-11). This represented 42 percent of the aramid rope's break strength and 34 percent of the steel rope's ultimate load. Testing of the rope after shock loading indicated that it had lost only 13 percent of its original strength.

Conclusions of the tests were that the parallel-fiber rope stored 75 percent more energy than a comparable steel cable for the same load and stretched 33 percent more for the same stored energy (Figures 2-12 and 2-13). The aramid rope had 48 percent more damping capacity than a similar steel cable.

Tests are now being planned at the Naval Research Laboratory to study the relative performance of different aramid fiber rope constructions and to compare their energy absorbtion capability to ropes of other materials.

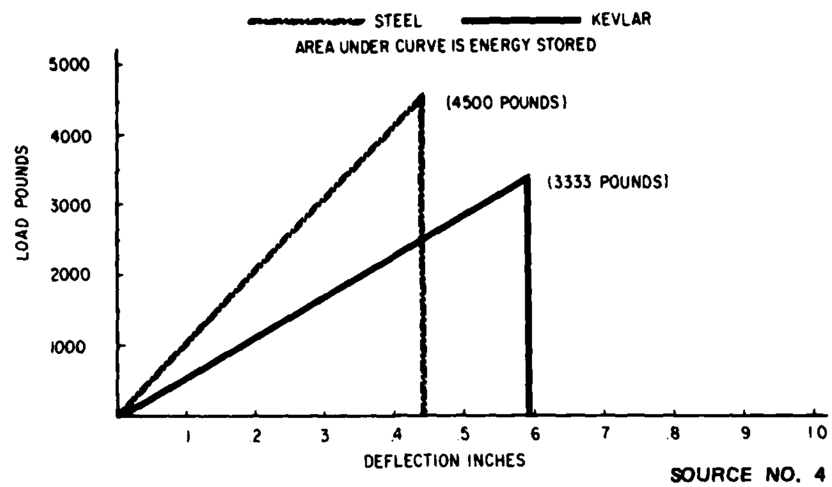

Figure 2-13 — Kevlar and steel displacement at equal energy stored

2-3. MECHANICAL TERMINATION. Termination of aramid fiber ropes requires special attention. Since the material has so little elongation and no yield, each element of the strength member must be proportionately loaded. If the strands of yarns are unevenly stressed, the one under the greatest strain will break first, then the next will take up the load and break, cascading until the last end gives. To obtain the maximum break strength of each rope, its termination must be carefully considered.

The type of rope, parallel, braid, or twisted, should be an influence on the type of end fitting to be used. Those available include epoxy potting terminals, splicing techniques, and some wire rope terminating hardware. At this point it must be remembered that Kevlar is a fiber. Thus, methods that have been used to terminate fiber ropes should be used to terminate the aramid. Usually, the best one to use is the one tested and recommended by the rope's manufacturer. Wall Rope Works has developed a method of splicing its parallel fiber rope (Uniline). This system employs the Chinese finger grip principle, which effectively doubles the amount of fiber at the end fitting and holds to 100 percent of the rope's break strength. It is easy to learn, can be accomplished in less than an hour, and will survive almost any type of loading.

The process is easily accomplished by simply removing several feet of the jacket on the end of the cable, separating the parallel strands or braid into four equal groups, forming an eye around a thimble, and then backbraiding over the standing part of the cable. The length of braid, number of crossings, and spacing have been carefully worked out to maximize the strength, and the resulting splice is normally served with yarn for protection. The thimble used should be the largest one feasible to accommodate the fiber's high strength and to avoid small bending radaii.

In effect, this type of end fitting doubles the number of strength members before the end fitting and produces a tapered, more rugged section at the eye. Therefore, near the eye, the stress per fiber should be about half that in the cable. A potted conical-socket end fitting, on the other hand, would impose the full load at the socket plus the additional sore point produced by transferring from a low moment of inertia to a high moment of inertia at the end fitting. Furthermore, very precise strand-length control is

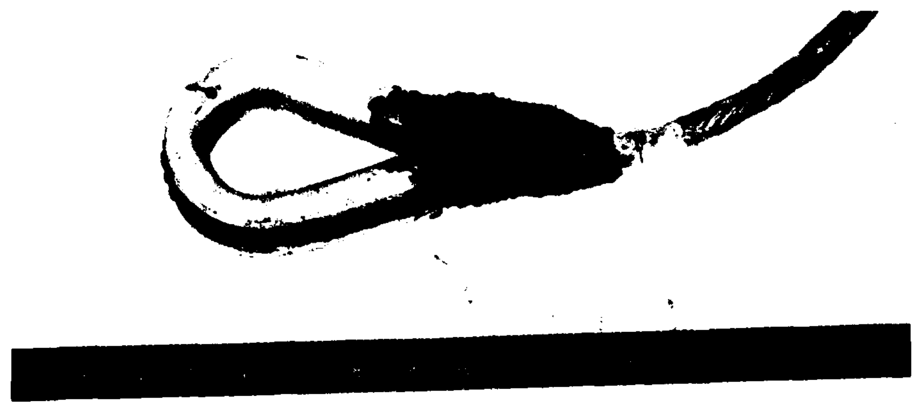

Figure 2-14 — Thimble and back-splice method developed by Wall Rope for Uniline

required during the application of the socket because little load sharing can be expected along the length of a properly made parallel cable. This class of end fitting is very practical and consistently results in test cables being broken at midspan at very high stress levels; their endurance of 100,000 impact cycles to 36 percent of the test cable breaking strength is ample testimony of their sturdiness. They are inexpensive and involve very little weight increase. Figures 2-14 and 2-15 are examples of mechanical and electromechanical end fittings made using this technique.

Philadelphia Resins Corporation utilizes an epoxy end fitting on their ropes. The rope is inserted into a cone-shaped potting fixture, broomed out, then cleaned. Epoxy resin is poured into the cone and cured, thus securing the rope into the fitting. These terminations will also develop 100 percent of the rope's break strength if proper care has been taken.

The potted end fitting is utilized on both braided and twisted aramid fiber ropes. Imperfections and minor length variations of the strands in the end fitting are easily adjusted to and accommodated by the multiple crossings in the braids or strands. Figures 2-16 and 2-17 are examples of two different potted end fittings.

Sampson Cordage Works describes an eye splice suitable for 2 in 1 braided rope. This relatively simple splice will develop 90 percent of the rope's break strength. A number of mechanical terminations which were originally developed for wire rope have also been used on fiber ropes with some success. However, it is recommended that the working load of ropes so terminated not exceed 20 percent of their breaking strength.

Work is presently being done on rope accessories such as end fittings, stoppers, and grips at the Naval Research Laboratory for example. At the present time, work is in progress to determine the optimum method of backbraiding to prevent slippage under various loading conditions.

A very good cable grip is easily formed from strands of impregnated Kevlar by forming an eye around a thimble with a group of parallel strands and dividing the strands into four equal bundles extending from the base of the eye. These can then be braided to the end of or along the length of any type of Kevlar cable or rope in much the same

Figure 2-15 — Thimble and back-splice method developed by Wall Rope for electromechanical cables. Small section of pipe welded between thimble arms allows safe exit of center conductors.

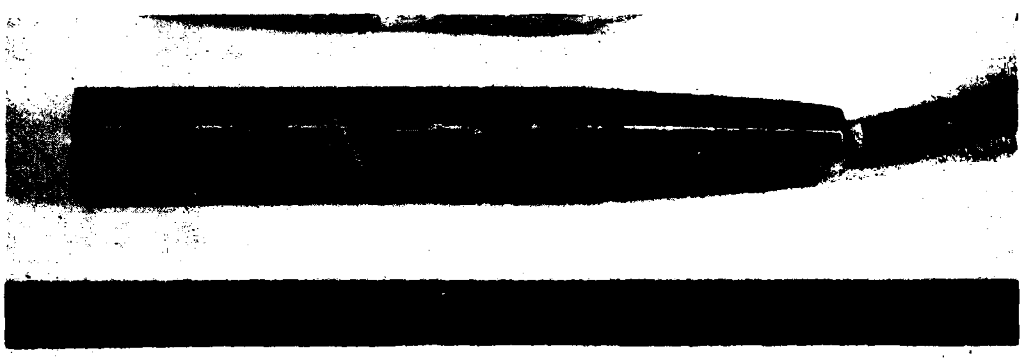

Figure 2-16 — Epoxy-potted conical socket used by Philadelphia Resins to pot braided rope

Figure 2-17 — Potted and served end fitting of a Moored Acoustic Buoy System (MABS) 12-triad cable fashion as the end fitting is accomplished for parallel construction. Therefore, the grip can be used as an end fitting or as a stopper; its strength can be made much greater than that of the line to be held, and it can be applied in a few minutes.

This type of grip has been used with the Moored Acoustic Buoy System (MABS) array at sea to attach the anchor at any location along the array without interrupting the cable. For example, where part of the array is to be vertical and part on the bottom, two grips are used — one leading the cable in each direction (for deployment considerations).

Speculation still persists that Kevlar cables are difficult to terminate or end fit, but this has not been found to be the case with either braids or parallel construction. Obviously, the right fitting must be chosen, and various percentages of breaking strength can be achieved with different choices of end fittings for applications that warrant a lower strength level. The various tests of breaking strength, long-term cyclic impact, and tension fatigue have shown that Kevlar cable and appropriate fittings perform very well.

2-4. SERVICE CONSIDERATION

2-4-1. Environmental. Kevlar 29 and 49 ropes have the features regarding environmental stability already covered in Chapter 1. The fibers have excellent resistance to a wide range of chemicals. However, as shown in Table 1-4, strong mineral acids and, to a lesser extent, concentrated bases will degrade the material. Prolonged exposure of aramid ropes to direct sunlight should be avoided. The aramids are sensitive to ultraviolet radiation, as are many other synthetic fibers (see Table 1-6). A Kevlar, three-strand rope shows percentage strength losses similar to those of nylon for equal-sized ropes.[19] The weakening effect of ultraviolet is not as pronounced in larger ropes, however, because the outer layers of material screen the inner fibers. However, an exposed rope should have a jacketing material of some sort which will also help protect against abrasion and mechanical damage.

Thermal stability of the aramid fiber is excellent for a temperature range of -50° to 400°F. Nevertheless, long-term service at temperatures above 300°F is not recommended, because oxidation effects weaken the material.[20] Figures 1-7, 1-8, and 1-9 show the resulting decrease in strength and modulus with increasing temperature. In contrast to other organics, Kevlar fibers have near zero shrinkage when heated. Moreover, cryogenic temperatures do not have adverse effects of any significance on the fiber. Table 1-5 listed the small change in properties with a 125°F change in temperature.

2-4-2. Abrasion Resistance—Fishbite on Buoy Mooring Lines. Because Kevlar is a fiber, the relative ease with which the fibers are cut and/or abraded in a transverse direction as compared to metal must be kept in mind. Its abrasion resistance is equivalent to that of nylon or polyester under wet conditions but is at least ten times worse under dry conditions. Table 2-6 lists the cycles to failure for ropes of three different synthetic materials when oscillated back and forth over an octogonal steel bar.[21]

[19] Riewald, P.G., Venkatachalam, T.K., "Kevlar Aramid Fiber for Rope and Cable Applications," Offshore Technology Conference, Marine Kevlar Cable Workshop, Houston, Texas, May 1975.
[20] Ibid.
[21] Ibid.

Table 2-6 — External Abrasion Resistance of 1/4-in.-Diameter Ropes
(Octagonal Steel Bar — 25-Lb Load, 30 cpm)

Item	Construction	Cycles to Failure	
		Dry	Wet
*Kevlar 29	Single Braid (16 picks/ft)	225	315
*Kevlar 29	Single Braid (30 picks/ft)	195	270
Dacron	2-in-1 Braid	1150	180
Nylon	2-in-1 Braid	—	135
Dacron	3-Strand	2380	570
Nylon	3-Strand	2900	690

*Kevlar 29 Without Lubricants

Source No. 1

Naturally, all ropes should be kept away from sharp and abrasive surfaces. Sheaves, drums, chocks, and bits can become scratched and gouged from previous use. If any synthetic fiber rope is the rub against a surface, the area should be carefully inspected and dressed down if necessary. Fixtures to be inserted into a rope such as terminations and thimbles should be examined for cutting edges.

Another possible mode of rope failure by cutting and/or abrasion is due to fishbite. There has been considerable discussion and speculation on this subject. Ten years ago a number of deep-sea mooring systems that had gone adrift were recovered with portions of the mooring lines intact. Several of the ropes were studied, and it was concluded that the failures were due to fishbite.[22] Since then, several papers have been published covering the various types of sea creatures involved in, and the depth-distribution of, the bites.[23,24]

On the other hand, the authors have never observed indications of fishbite on acoustic measurement arrays deployed in various parts of the Pacific, Atlantic, Mediterranean, and Carribean areas. The differing observations are not necessarily contradictory, however, because a distinctive difference exists in the mooring systems involved. One system supports hydrophones, and is designed to remain motionless and quiet. The other system, on which most fishbite has occurred, consists of unfaired mooring lines for surface follower buoys. It appears that fish do not tend to bite cables that do not strum. During the

[22]Stimson, P.B., "Synthetic-Fiber Deep-Sea Mooring Cables-Their Life Expectancy and Susceptibility to Biological Attack," Deep-Sea Research, 1965, 12, pp. 1-8.
[23]Turner, Harry J., Jr., Prindle, Bryce, "Some Characteristics of Fishbite Damage on Deep-Sea Mooring Lines," 65-22, Woods Hole Oceanographic Institution, Woods Hole, Mass., April 1965
[24]Turner, Harry J., Jr., Prindle, Bryce, "The Vertical Distribution of Fishbites on Deep-Sea Mooring Lines in the Vicinity of Bermuda," Tech. Rpt. 67-58, Woods Hole Oceanographic Institution, Woods Hole, Mass., Oct. 1967.

past 3 years, particular attention has been paid to fishbite by carefully examining the various arrays and mooring lines during recovery. Yet not a single bite has been observed. Most of the arrays have been subsurface buoy systems in deep water with the buoy placed less than 1,000 feet below the surface. Several systems have been surface-supported, but considerable care was taken to decouple the surface motion. All have utilized some type of cable fairing.

This is not conclusive evidence, however, and considerable conflicting information exists. Explicit experiments will be required to determine whether fish bite motionless cables. Until then, one should proceed with caution in utilizing synthetic cables through the fish-bite zone.

Lastly, the construction of the rope must be included as an important factor in its resistance to wear and cuts when comparing various ropes of equal size and material. For example, the eight-ply will concentrate its weight on the knuckles of the weave. However, a braid or a twisted rope (19 X 7) of many strands will distribute the load and abrasion over more of the surface area.

2-4-3. Biodegradation. An additional problem that might be encountered, especially near shore, is encrustation of the exposed fiber with marine life. A number of samples of aramid fiber rope were exposed at a depth of 18 feet in a Hawaiian bay[25]. After six months, they exhibited a calcareous growth which was easily removed. The tensile strength and modulus of the exposed samples remained unaffected.

However, after a twenty month exposure of other similar samples, the rope became heavily encrusted, and the filament helix was disrupted where larger barnacles had attached themselves. Testing revealed a 40-percent reduction in tensile strength. It must be emphasized here that these samples were not jacketed and were exposed in coastal waters.

2-4-4. Handling and Safety Factors. At this time it is impossible to set exact safety factors for aramid fiber ropes. Not even the wire rope industries with their years of experience have been able to do it. The proper factor depends not only on the rope, its construction and its material, but also on the loads applied, speed of operation, end fittings used, acceleration and deceleration, length of rope, number and size of sheaves and drums, duration of rope usage, the abuse it has had during that time, and most important, the possible loss of life and property should that rope fail. At this point some guidelines can be provided, but as experience is gained, changes may be required. The basic recommendation for ordinary usage of an aramid fiber rope is a safety factor of 5:1. That is, the breaking strength of the rope should be five times as great as the largest expected load on the rope.

As previously mentioned in this handbook, the ratio of sheave diameter to rope diameter is very important. To prolong a working rope's lifetime, the sheave diameter should be as large as possible. Braids and twisted aramid fiber ropes should have a ratio in the neighborhood of 25:1. Parallel-strand ropes require a much larger diameter; the closer this ratio is to 50:1, the better it is. These proportions must be varied according to the aforementioned variable factors and would also apply to capstans, drums, and various types of cable-tensioning machinery.

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[25] Wilkins, George A., "Performance Characteristics of Kevlar-49 Tension Members," Naval Undersea Center, Kailua Hawaii, 1975.

Storage of synthetic fiber ropes under tension on a drum or reel is not a good practice, and various types of cable-tensioning machinery are available to relieve any stresses in the rope prior to spooling. If however it is necessary to wind onto a drum under tension, the ideal situation would be to have no more than one layer. This is impractical for oceanographic purposes. Assuming a need to spool many layers of rope under tension, several red flags must be raised. One, to avoid excessive chafing of the rope, it is desirable to keep the fleet angle as small as possible. Two, in the case of twisted fiber rope, it is important to wind the rope onto the drum in the proper direction of lay, otherwise the rope will tend to unlay and kink if tension is temporarily removed. This does not pertain to parallel-lay or braided ropes. And, three, if enough layers are spooled under enough tension, the radially directed force will become greater than the compression strength of the material, thereby crushing the innermost layers.

A unique method of deploying and retrieving aramid fiber arrays has been developed and used by the Systems Engineering Staff of the Naval Research Laboratory. The braided Kevlar rope which includes electrical wires, hydrophones, and fairing is stored in a wooden box. The line is fed by hand from the box to a large-diameter V-grooved sheave which is fixed to a capstan. The powered sheave's groove provides sufficient tension on the rope to lower or raise the array. The box provides the necessary storage area and protection. There is no complicated deck machinery needed.

The decision as to the proper time for removal of a rope from service is a difficult one. Presently there is no definite answer. Tensile tests of worn ropes from various installations would be the only way of accumulating enough data to allow reasonably close estimates to be made.

CHAPTER 3. ARAMID FIBER ELECTROMECHANICAL CABLES

3-1. CONSTRUCTION AND APPLICATION. Primarily, it is the fact that both Kevlar 29 and Kevlar 49 have very low elongation under load which has enabled this fiber to succeed as a strength member in electromechanical cable. The elongation of the aramid fibers at break strength is 4 percent for Kevlar 29 and 2.4 percent for Kevlar 49. This relatively small amount of stretch makes it possible to include properly designed electrical conductors within the synthetic fiber cable.

Second on the list of merits must be the material's high tensile strength. It is because this aramid has an ultimate load of 400,000 lb/in.^{2} that it is in contention with steel, whose ultimate strength is in the order of 300,000 lb/in.^{2}. Of course, as with all the various fibers and wires used to make rope, the ultimate strength of the cable depends on the conversion efficiency of the construction chosen. Nevertheless, for similar construction and equal size, the tensile strength of the aramid fiber compares favorably with other cable strength members.

If we now merge the fiber's great tensile strength and high modulus with its light weight, it becomes apparent that, at this time, Kevlar has the best strength-to-weight ratio of all conventional cable materials (see Figure 1-5). With a density of only 0.052 lb/in.^{3}, this ratio is 7 times greater than steel in air and twenty times greater in water.

Due to the fiber's low specific gravity, aramid cables can be made neutrally bouyant just by the prudent choice of materials used for conductor insulation and/or for cable filler and jacketing. Hence, there may be no need for the flotation modules sometimes necessary in systems utilizing steel electromechanical cables. The benefits include reducing handling and storage problems, avoiding the additional drag, and eliminating any implosion hazards sometimes caused by buoyance modulus.

The Kevlar electromechanical cable possesses numerous possibilities for design variation such as type of strength member, sensor location, size and number of electrical wires, conductor insulation, position of conductors relative to strength members, and jacketing material. Properties of the aramid fiber rope have already been covered in the last chapter. Therefore, this chapter will discuss the features of the aramid fiber that relate to electromechanical cable. (For a more comprehensive coverage of the development of aramid fiber electromechanical cable, see NUSC Report 4915[1]).

3-1-1. Helically Wrapped Strength-Member Cables.[5] A Kevlar 49 twisted strand, electromechanical cable has been developed by the Naval Undersea Center.[2] After a number of

[1]Swenson, R.C., "The Cable Development Program for Suspended Sensor Applications," NUSC Technical Report 4915, New London, Connecticut, 1975.

[2]Wilkins, George A., Performance Characteristics of Kevlar 49 Tension Members, Proceedings of the International Conference on Composite Materials, Geneva, Switzerland, April 7-11, and Boston, Mass., April 14-18, 1975.

tests on the prototype cable, several suggestions concerning the fiber and its handling were put fourth:[3]

(a) Very tight quality-control procedures must be followed in the production state. Each change of technique or material should be accompanied by tests.

(b) To assemble this type of cable, most U.S. companies utilize machines designed for use with steel wire. Several modifications are necessary before they are suitable for use with aramid fiber.

(c) Cables will possess some degree of torque.

3-1-2. Braided Strength-Member Cables. Braided strength-member electromechanical cable appears to have some outstanding characteristics both in and out of the ocean. Its principal merits include those of braided mechanical ropes with a few additional ones:

(a) Ease of fabrication, which requires considerably less precision than alternative constructions.

(b) Complete torque balance.

(c) Self-limitation of the effects of yarn damage. Local imperfections and individual yarn damage are averaged over a short length of the cable. Even if each yarn is cut many times along the length of the cable, only a slight decrease in cable strength will result as long as the cuts are separated by several feet.

(d) Ease of end fitting by eye splicing or with epoxy-potted conical sockets.

(e) Accommodation of a wide variety of core sizes.

(f) A wide range of strengths through choice of yarn sizing, braid design, and number of layers.

(g) Excellent cyclic-tension fatigue life at high stress levels.

(h) Low elastic stretch that can be easily accommodated by properly designed conductors.

(i) Flexibility and small bending radii.

(j) Excellent cost effectiveness within certain ranges in relationship to alternative materials and strength requirements.

(k) New sensor mounting designs have made it possible to insert sensors into a braided electromechanical cable without cutting or end-fitting the cable.

Yarn failure, due to abrasion and compression, has been alleviated by the use of untwisted impregnated yarn. This does not refer to the slight amount of yarn twist necessary to improve the yarn's strength and abrasion resistance but rather to the yarns which have

[3] Wilkins, G.A., Hightower, J.D., Rosencrantz, D.C., "Lightweight Cables for Deep Tethered Vehicles," Proceedings of the Ocean 75 Conference, San Diego, California, September 22-25, 1975

twists an order of magnitude higher. The untwisted yarns tend to flatten out at the crossovers, thereby reducing the crimp angle and distributing the compressive load. Aramid cables of this type have sustained a million tension cycles at loads up to 180,000 lb/in.^{2} without strength reduction.

The abrasion resistance of the fibers due to cycling over sheaves has been a problem. A slight twist and impregnation with urethane initially improved the yarn's self-abrasion problems but did not eliminate it. Recent results published by Du Pont indicate a large increase in the wear life of the fiber by using wax overlays (see Section 1-3-2)[4] However, some additional testing will be necessary before results are conclusive.

The electromechanical cables are constructed by weaving one or more layers of braid over one or more electrical conductors. The mechanical break strength of the cable cable then depends on the braid helix angle, crimp angle, ends per carrier, etc. (see Section 2-1-2), and on the layers of added braid. Final options include incorporating fairing into the last weave, substituting a jacket of a more abrasive resistant fabric on the last weave, or extruding a polyurethane jacket over the entire assembly.

An example of a braided electromechanical cable that has performed well is one currently in use in oceanographic acoustic systems. It is a thirty-six conductor, electrically tapered hydrophone array cable with a break strength of 19,200 pounds. Data from load elongation curves indicate that the linear elongation is 1.26 percent at 8,000 pounds and only 0.3 percent at working load.

Basically, the array cable consists of four braided cables with nine electrical conductors in each cable. The four cables were assembled and overbraided incorporating an anti-strumming fairing into the jacket. Upon completion, the outside diameter was 7/8 inch. The finished product along with its in-line hydrophone cage is shown in Figure 3-1.

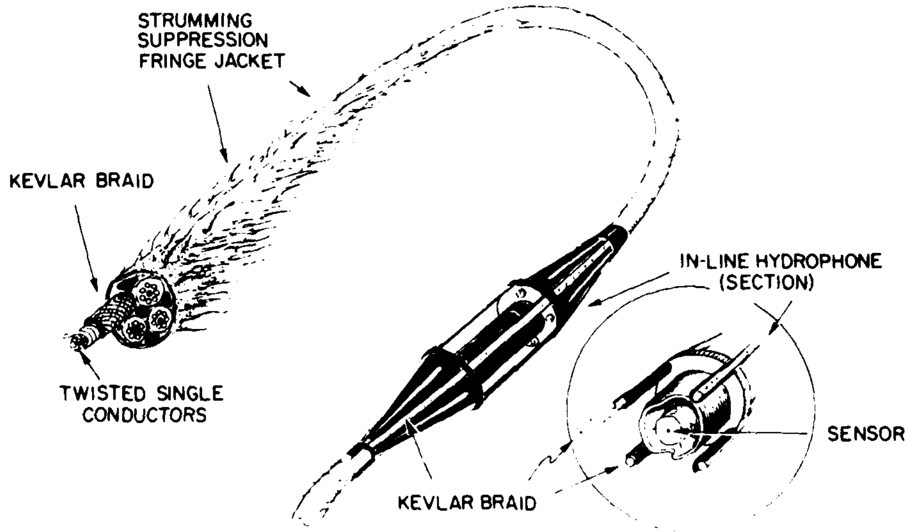

Figure 3-1 — Four-strand Kevlar hydrophone cable

[4]Riewald, P., unpublished preliminary report, "Abrasion Resistance of Kevlar 29 and Kevlar 49 Impregnated Yarns," February 1976.

Because the instrumentation is uniformly spaced along the cable, it is possible to taper the electrical conductors along the 6,000-foot length. This tapering reduces both the cost and the weight of the array. A thermoplastic, rubber-filled rod is used in place of the absent conductors so as not to deform and weaken the braid (see Figure 3-2).

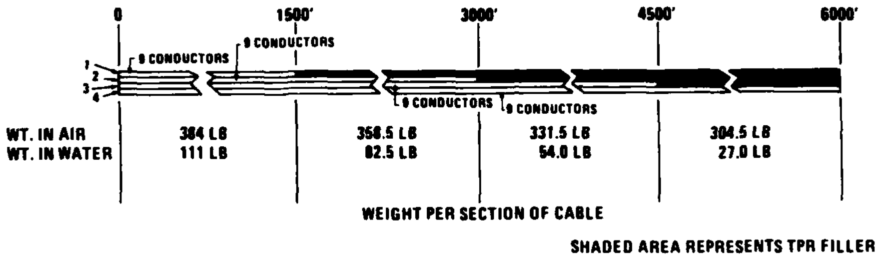

Figure 3-2 — Braided four-strand Kevlar cable

From our testing and experience, it appears that aramid braid provides excellent strength member construction for electromechanical cable.

3-1-3. Parallel Strength-Member Cables. The parallel-strand electromechanical cables tested and used to date have performed exceptionally well and represent a significant step forward in ease of sensor array fabrication and operation. However, caution must be exercised that they are not used for other than the intended design application. Here, as with parallel-strand mechanical ropes, considerable care is required in fabrication in order to establish equal loading on all strands and to produce a good, firm, well-bodied cable. with good handling characteristics.

With this parallel-strand approach, it becomes a fairly easy task to bring out the conductors at any point along the cable for instrumentation attachment. Or, as in the case of specially designed sensors, the cable can be opened, the instrument inserted into the center of the cable, and the strength members run alongside the instrument case. Either method eliminates the problems associated with cutting and end fitting the cable at each sensor location.

A typical parallel aramid fiber electromechanical cable is the 4,600-foot, six-element Uniline, which was designed and fabricated for the Moored Acoustic Buoy System (MABS). Three conductors were twisted together to form each triad. Six triads were cabled around a 0.165-inch-diameter thermoplastic rubber (TPR) core. The assembly was then covered with two layers of 1-mil Mylar tape, resulting in a 0.42-inch-diameter electrical core.

The strength members consisted of 34 12,000-denier latex-rubber-impregnated Kevlar 29 strands parallel with and around the electrical core. This assembly was wrapped with two layers of neoprene tape and braided over with a polyester jacket, which included tufts of polypropylene fringe fairing at 1-inch intervals. The cable had a diameter of 0.75 inch, a weight of 0.22 lb/ft in air, and 0.066 lb/ft in water, and a measured breaking strength of 14,130 lb/ft (see Figure 3-3).

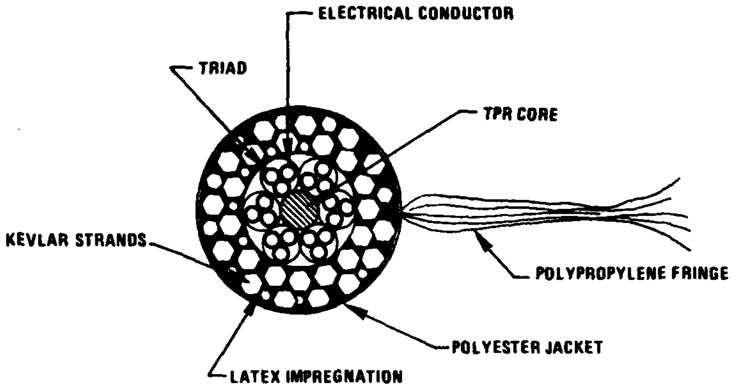

Figure 3-3 — Parallel-strand electromechanical cable

The in-line hydrophones were inserted into this cable while it was being coiled into a pressure tank; 3 hours were required to mount each hydrophone. Single-pin, slip-on connectors were used to seal the conductors to the hydrophones. The array was then pressure-tested, found to be free of faults, coiled in a crib, and shipped for loading on board ship.

During the subsequent deployments, the array was coiled on deck and snaked off the deck during anchor free-fall, payed out directly from the crib, and spooled onto a deck winch. Multiple handling produced no indications of weakness in the design for this application. After final recovery, the array was coiled back into its crib with one end available for buoy attachment and the other for anchor attachment if another deployment was required. Payout speeds from 100 to 200 feet per minute have been used. Performance, both mechanical and acoustical, has been excellent.

After 6 months aboard ship the array was in excellent condition. No deterioration or corrosion was evident. It was then cut in half; the lower section was coiled in a 4-foot cube box and air freighted to Australia, while the upper section was placed in storage. The array can be rejoined, operated as two individual six-element arrays with the addition of more hydrophones, or operated as a 12-element array with the instrument-vessel placed in the center.

The array section shipped to Australia was reconfigured as a six-element array (by the addition of three hydrophones) and used for a surface-supported sensor system. It was deployed and recovered three times by hand, without the use of any deck machinery, in conditions of 20-to-35-knot steady wind. Acoustic performance of the system in these adverse conditions was excellent, and logistic expense of the operation was minimal.

A sample of this cable was subjected to the same laboratory testing as previously described. Both the breaking strength and sheave life were significantly less than for the previous cables, but the proportionately larger electrical core, along with the use of ordinary conductors, undoubtedly contributed to that result. However, the actual 14,000 pounds breaking strength provides a static safety factor of greater than 10, and 794 bending cycles at 2500 pounds tension far exceeds the envisioned life requirements for the service intended.

The Woods Hole Oceanographic Institute purchased a 15,000-foot continuous length of this cable and used it with their Acoustic Data Acquisition Capsule system. A 15,000-

foot, six-element-array cable was formed by opening the cable jacket, separating (without cutting) the strength members, extracting the appropriate color-coded triad, and installing slip-on connectors. The hydrophones were attached and removed during deployment and recovery, respectively, by clamping them to the cable. The location of hydrophone placement was easily found, since the cable is permanently marked at 100-foot intervals with colored tufts in the fringe fairing. This occurs while the cable is under tension during the cabling process. The cable was then wound on a large winch.

3-2. COST CONSIDERATIONS. In designing a cable for suspended-array applications, one must consider array fabrication, testing, calibration, handling, deployment, reliability, and performance in terms of overall system cost. Considerable final-system cost savings can be realized if the optimum fit can be found between the materials available and the performance required. The costs are much harder to identify than simply being the bare cost per foot of cable. For example, in comparing two 10,000-foot long six-element arrays for the MABS, one of round wire armor steel and the other of Kevlar 29, one finds that the steel cable costs $1.00 per foot, while the Kevlar cable costs $2.00 per foot. However, the costs of the same two cables, faired and rendered neutrally buoyant by the addition of syntactic foam floats, are $5.50 per foot and $2.74 per foot, respectively. Also, because of the ease of making the Kevlar array and because negligible additional buoyancy is required to compensate for the weight associated with sensor attachments, the final, finished array costs are $75,000 for steel and $31,400 for Kevlar. Furthermore, the lead time required for assembling the Kevlar array is less than half that for steel, the performance and versatility of the Kevlar array are greater, and the maintenance and replacement costs of the Kevlar array are considerably lower.

Over and above these basic costs, one must compare the operational costs of the two systems. Experience indicates that this is where Kevlar cables produce major savings. Some of these considerations are the number of personnel required (including the number of berths on the deployment vessel), the winching requirements, deck and storage space requirements, total weight, weather dependence, and array life, (For example, the steel MABS array failed during its first season of use, although it was repaired, as a result of dynamic loading during recovery. However after one season of usage, the Kevlar array appears to be in new condition with no signs of deterioration or damage.)

GLOSSARY

(Terms As Used In This Report)

Array	An assembly of instruments, such as hydrophones or thermistors, distributed along, supported by, and communicated with by means of an electromechanical cable.
Compliance	The degree to which a cable can elastically elongate to reduce the effects of dynamic loading.
Creep	Permanent time-dependent elongation of a cable under load (as distinct from, and in addition to, elastic elongation).
Denier	Weight in grams of a 9000-meter length of fiber yarn or filament.
Elastic Modulus	Ratio of unit stress to unit strain within the elastic limit of the material.
End	Similar to strand.
Fiberglass	A rope fiber occasionally used when total fire-resistance is required. It has very low elongation and very high strength but has poor resistance to flexing, is susceptible to fatigue, and deteriorates in water.
Filament	A fiber of extreme length, manufactured by an extrusion process. Many filaments contained in one bundle out of one extrusion process are called multifilaments. A filament which has a diameter over 0.1 mm or 4 mils is called monofilament.
Kevlar	Du Pont trademark for a new high-strength, low-stretch aramid fiber (formerly called PRD 49 and Fiber B).
Kink	A knot, back turn, or loop drawn tight in a cable, generally caused by the release of stored torsional energy during tension relaxation.
Lay	The length of a complete turn of a strand in a rope or cable.
Nylon	High-tensile-strength high-elasticity abrasion-resistant fiber with excellent energy absorption and impact resistance. Immersion in water lowers its strength and increases elongation.

Polyester	Generic term for a family of fibers manufactured under various trade names: Dacron (Du Pont), Fortrel (Celenese), Kodal (Eastman). Polyesters have high tensile strength, low elastic elongation, and excellent abrasion resistance.
Polypropylene	A fiber made in either monofilament or multifilament form. Its strength is approximately 60 to 75 percent that of nylon and polyester. It is a lightweight fiber with high positive buoyancy. It is not as abrasion resistant as polyethylene and is a poor working line.
Polyethylene	A lightweight high-buoyancy fiber with about 5 percent less strength than polypropylene and 5 percent heavier.
Serving	Helically wrapped strands or yarns around a cable core (as for armored steel cable or for protection at fittings).
Strand	Fibers or yarns twisted and/or impregnated to form a strength-member building block for ropes or cables.
Tenacity	The breaking strength of a yarn in grams force divided by the denier of the yarn.
Twist	The number of turns per inch in a yarn.
Yarn	A longitudinal group of fibers with or without twist.
Yarn Diameter	$= \frac{\text{filament diameter X } \sqrt{\text{no. of filaments}}}{0.91}$, where 91 is the packing factor.

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